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APTI (Air Pollution Training Institute)
Course 413: Control of Particulte Emissions
Instructor's Guide

Northrop Services, Inc.
Research Triangle Park, NC

Prepared for

Environmental Protection Agency
Research Triangle Park, NC

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Air

APTI
Course 413
Control of Particulate Emissions

Instructor's Guide

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Under Contract No.
68-02-2374
EPA Project Officer
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United States Environmental Protection Agency
Office of Air, Noise, and Radiation
Office of Air Quality Planning and Standards
Research Triangle Park, NC 27711

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16. ABSTRACT

The Instructor's Guide for the Air Pollution Training Institute Course 413, "Control of Particulate Emissions," contains complete information for conducting a 4 day course in particulate emissions control. The Guide contains course goals and objectives, preparation instructions, lesson plans, exams and exam keys, solutions to problem sets, and copies of handout materials. The lesson plans include keys to 35mm slides developed for the course and suggested instructional techniques.

This Guide is intended for use in conjunction with the Student Manual (EPA 450/2-80-066) and the Student Workbook (EPA 450/2-80-067) for APTI Course 413.

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AIR POLLUTION TRAINING INSTITUTE
MANPOWER AND TECHNICAL INFORMATION BRANCH
CONTROL PROGRAMS DEVELOPMENT DIVISION
OFFICE OF AIR QUALITY PLANNING AND STANDARDS

The Air Pollution Training Institute (1) conducts training for personnel working on the development and improvement of state, and local governmental, and EPA air pollution control programs, as well as for personnel in industry and academic institutions; (2) provides consultation and other training assistance to governmental agencies, educational institutions, industrial organizations, and others engaged in air pollution training activities; and (3) promotes the development and improvement of air pollution training programs in educational institutions and state, regional, and local governmental air pollution control agencies. Much of the program is now conducted by an on-site contractor, Northrop Services, Inc.

One of the principal mechanisms utilized to meet the Institute's goals is the intensive short term technical training course. A full-time professional staff is responsible for the design, development, and presentation of these courses. In addition the services of scientists, engineers, and specialists from other EPA programs governmental agencies, industries, and universities are used to augment and reinforce the Institute staff in the development and presentation of technical material.

Individual course objectives and desired learning outcomes are delineated to meet specific program needs through training. Subject matter areas covered include air pollution source studies, atmospheric dispersion, and air quality management. These courses are presented in the Institute's resident classrooms and laboratories and at various field locations.

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Instructions for Preparation and Presentation of Course #413

Control of Particulate Emissions

This guide is to provide you as Course Moderator with assistance in the preparation and presentation of Course #413 - Control of Particulate Emissions. It will provide you with guidelines, instructions and some general information that should facilitate your efforts in staging this course.

I. Course Description and Prerequisites

This training course is a four-day lecture course dealing with the mechanisms and design parameters of devices for control of particulate emissions to the atmosphere. Major emphasis is placed on basic theory, with problem sessions in which the student calculates the effects of particle size distribution on efficiency and determines the efficiency of devices such as wet collectors, cyclones, fabric filtration systems and electrostatic precipitators. Knowledge gained in the course will assist the student in reviewing plans and specifications for particulate emission control systems with respect to their probable effectiveness, and in making inspections of installations with operating particulate emission control devices.

II. Background, Origin, and Philosophy

The Environmental Protection Agency Air Pollution Training Institute (APTI) provides courses in air pollution control technology, ambient and source monitoring, and air quality management. In July, 1976, Northrop Services, Inc. was contracted to both present Training Institute courses and to provide support and technical services for the Institute as a whole. Courses of particular importance to governmental and industrial personnel concerned with air pollution problems received early efforts of instructional development to design the best possible training experiences for the students. This required thorough examination of both the materials for instruction and an examination of the characteristics of the student audience. From such studies, the courses have been revised and developed to provide training that enables every student to achieve specific course objectives.

The students attending Course 413 generally characterize themselves as engineers and are employed by a federal, state, or local pollution control agency. The student makeup for attendees in seven course offerings from October 1, 1978 through September 30, 1979 was as follows:

Profession	Percent
Administrator	1.0
Chemist	3.9
Engineer	63.2
Meteorologist	1.0
Physical Scientist	3.2
Sanitarian	2.3
Statistician	0.3
Technician	7.5
Others	17.6
	100.0

Employer	Percent
Federal EPA	19.9
Other Fed. Gov.	1.9
State Gov.	50.5
Local	15.6
Industry	9.8
Consultant	2.0
Others	0.3
	100.0

Educational Background	Percent
High School	12.7
Bachelor	63.2
Master	22.8
Ph.D.	1.3
	100.0

Years Experience	Percent
0 - 1	35.5
2 - 4	27.0
5 - 7	20.9
8 - 10	11.7
> 10	4.9
	100.0

The course has been designed for the engineer in a governmental air pollution control agency. The course records indicate that the attendees are in fact those for which the course has been developed. This instructional package has therefore been prepared with this student population in mind.

Student intellectual studies performed during the initial contract year have indicated that for APTI courses, the course content and instructional methods should be explicit rather than implicit. Although formal educational level tends to be generally high, the ability testing has indicated the need for the course content to be presented in a careful and logical and consistent order with the underlying principles and relationships of given concepts being taught directly. At critical junctures where students are required to visualize a concept, infer a relationship, or visualize an added dimension, instruction is mediated with the use of:

- Graphic illustrations, usually in the form of 35mm slides
- Lecture demonstrations
- In-class problem-solving sessions
- Constant repetition and review of fundamental concepts.

III. Instructions for Preparation and Presentation of Course

A. Responsibilities of Course Moderator

This course generally requires 4 days for a complete presentation. It can also be expected 10 to 20 hours of additional preparation will be required by the individual designated Course Moderator. Preparation and continuity are the principle responsibilities of the Course Moderator who will coordinate all on-site activities both before and during the course presentation. The actual tasks that are considered the direct responsibility of the Course Moderator are:

1. Scheduling the course presentation
2. Recruiting (hiring) and briefing instructors
3. Preparation of classroom and teaching facilities
4. Preparation of and distribution of course materials
5. Presentation of introduction and other appropriate lectures
6. Maintaining continuity throughout the course.

B. Scheduling

The course itself is designed around a format using 14 lectures and 7 problem sessions, all of which are designed to fit into a 4 day time frame of morning and afternoon classes. Because the course contains a concentrated level of involvement with rather technical material, it is recommended that no more than seven (7) hours of class instruction be presented in one day.

This Instructor's Guide contains lesson plans for all instruction, each listed below with its recommended time and schedule placement.

DAY 1

	Welcome and Registration	30 minutes
Lesson 1	Review of the Basics	90 minutes
Lesson 2	Particle Dynamics	60 minutes
Lesson 2a	Problem Session I - Particle Dynamics	30 minutes

Lesson 3	Particle Sizing - Measurement and Mathematical Methods	60 minutes
Lesson 3a	Problem Session II - Particle Sizing	30 minutes

DAY 2

	Homework Review	30 minutes
Lesson 4	Methods for Reducing Particulate Emissions	30 minutes
Lesson 5	Settling Chamber: Principles, Operation and Applications	30 minutes
Lesson 5a	Problem Session III - Settling Chamber	15 minutes
Lesson 6	Cyclones: Principles, Operation and Applications	45 minutes
Lesson 6a	Problem Session IV - Cyclones	45 minutes
Lesson 7	Electrostatic Precipitator Principles and Operation	75 minutes
Lesson 8	ESP: Design and Applications	60 minutes
Lesson 8a	Problem Session V - Electrostatic Precipitator	60 minutes

DAY 3

	Homework Review	15 minutes
Lesson 9	Fabric Filter Principles	90 minutes
Lesson 10	Fabric Filter Applications	30 minutes
Lesson 10a	Problem Session VI - Fabric Filter	60 minutes
Lesson 11	Wet Collector Theory	75 minutes
Lesson 11a	Problem Session VII - Wet Collector	60 minutes
Lesson 12	Wet Collector Design	60 minutes

DAY 4

	Homework Review	30 minutes
Lesson 13	Operations Maintenance and Inspection of Air Pollution Control Equipment	60 minutes
Lesson 14	Estimating the Cost of Control Equipment	60 minutes
	Pre-test Review	45 minutes
	Course Overview	30 minutes

C. Instructors

The four most important criteria in the selection of faculty for this course are:

1. A knowledge of the current methods and procedures used in control of particulate emissions
2. Recent practical experience
3. Experience (and ability) to instruct adults using traditional and non-traditional methods, materials, and techniques
4. A positive attitude toward air quality management.

Before instructors are actually involved with instruction in the classroom, the Course Moderator should conduct thorough briefing and preparation sessions in which an overview of the entire course presentation is given. Specific discussion of course and lesson objectives should result in an assurance that the instructors are well prepared and familiar with the materials, procedures, and techniques that they will be using.

The Course Moderator should stress the difference in the role that the instructor plays as compared to traditional university instruction situations. All instructors should fully understand the function of the course and lesson objectives and the relationship of each objective to their particular materials and to the pre- and post-testing.

It may be particularly helpful to the instructors if they are able to sit in on early sessions of the course presentation, so that they get a feel for the way the students are oriented to the material and be able to incorporate the strengths and background experiences of the students into the various instructional sessions.

Preparation must be stressed to all prospective instructors. Thorough familiarization with all the prepared materials is essential for even "expert" instructors. Problem sessions require additional preparation and should include a complete run-through to check out the methods used before presenting them to the students.

D. Physical Setting

Classroom - 1200-1500 sq. ft. to accomodate 38-40 people (34-36 students, 3 instructors, 1 evaluator); all students should have desks or tables - others need chairs only
- 35mm slide projector
- overhead projector
- screen at least 6 feet by 6 feet
- chalk board, erasers and chalk

E. Course Materials

In addition to the course lecture and lesson outlines, the pre-test, post-test, keys, and the audiovisual materials provided with this instructor's guide, this package also contains the following materials:

1. APTI Course 413 Student Manual, EPA-450/2-80-066
2. APTI Course 413 Student Problem Workbook, EPA-450/2-80-067

F. Audiovisual Materials

The visuals package accompanying these materials includes 384 35mm slides. The specific lessons are as follows:

Lesson 1	33 slides	413-1-1	through	413-1-33
Lesson 2	30 slides	413-2-1	through	413-2-30
Lesson 3	36 slides	413-3-1	through	413-3-36
Lesson 4	14 slides	413-4-1	through	413-4-14
Lesson 5	13 slides	413-5-1	through	413-5-13

Lesson 6	15 slides	413-6-1	through	413-6-15
Lesson 7	39 slides	413-7-1	through	413-7-39
Lesson 8	34 slides	413-8-1	through	413-8-34
Lesson 9	45 slides	413-9-1	through	413-9-45
Lesson 10	9 slides	413-10-1	through	413-10-9
Lesson 11	44 slides	413-11-1	through	413-11-44
Lesson 12	39 slides	413-12-1	through	413-12-39
Lesson 13	33 slides	413-13-1	through	413-13-33
Lesson 14	no slides			
TOTAL	384 slides			

Complete listings of the slides for each lesson are included with the lesson plans. These slides are either supplied as a part of the instructional resource package or are available on loan for reproduction through the Air Pollution Training Institute.

G. Lesson Plan Use

Each lesson plan module is designed to serve as:

A. Source of lesson objectives
B. Content guide for instructor
C. Lecture outline
D. Directions for use of visual aids
E. Guidelines for approach to the lesson.

Generally, the lesson plans are organized as straight outlines with additional instructions and keys to the visuals found on the right hand border of the page. On occasion it was felt that the instructor might need more specific information and a more narrative format is used for the subject matter to be adequately covered.

Each lecture plan outline is carefully timed. Instructors should give attention to observing time schedules and "pace" of the lessons to be given.

Instructors must be familiar with the visual aids and handout materials before attempting to present any lesson.

The visuals are keyed using number references that are also found on the slides. The number identifies the lecture and sequence of the slide. Thus, 413-16-5 identifies a slide in Lecture 16 that comes before 413-16-6 and after 413-16-4. Also, each slide is provided with a "thumb spot" that should be in the upper right hand corner of the frame (under your thumb) as the slide is loaded into a carousel. This should prevent slides from being loaded backwards or upside-down.

Instructors may wish to vary slightly from the format or content for a given lesson, but should be cautioned that the schedules and lesson objectives must be maintained. Variations should be in the direction of greater student participation. Instructors should remember that the exams reflect the lesson objectives as presented through these lesson outlines.

H. Grading Philosophy

The guidelines for grading student's performance in "Control of Particulate Emissions," and granting Continuing Education Units (CEU's) are as follows:

The student must:

- attend a minimum of 95% of all scheduled class sessions
- complete and hand in copies of all homework = 10 points
- achieve average course grade of 70%
  course grade = final exam score + homework points

I. Other Logistics

Since the Course Moderator will need to consider a great variety of logistic and instructional concerns, the following checklist is provided to serve as a guide to meeting these responsibilities.

The course developers have tried to provide you with as much information and materials as possible to enable you to present a successful and exciting educational venture.

CHECKLIST
OF ACTIVITIES
FOR PRESENTING THE COURSE

A. Pre-course Responsibilities:

_____ 1. Reserve and confirm classroom(s) and laboratories, including size, "set-up", location and costs (if any).

_____ 2. Contact and confirm all faculty (speakers) for the course(s), including their AV requirements. Send material (i.e., slides and instructor's manual) to them. One or more pre-course instructor's meetings are advisable.

_____ 3. Reserve hotel accommodations for faculty.

_____ 4. Arrange for and confirm food service needs (i.e., meals, coffee breaks, water, etc., if appropriate).

_____ 5. Prepare and reproduce final ("revise" if appropriate) copy of the detailed program schedule.

_____ 6. Reproduce final registration/attendance roster, including observers (if any).

_____ 7. Prepare name badges and name "tents" for students and faculty.

_____ 8. Identify, order, and confirm all AV equipment needs.

_____ 9. Prepare two or three 12 in. x 15 in. signs on posterboard for posting at meeting area.

_____10. Arrange for and confirm any special administrative assistance needs on-site for course, including "local" Address of Welcome, etc.

_____11. Obtain copies of EPA manuals and pamphlets.

_____12. Pack and ship box of supplies and materials one week prior to beginning of course (if appropriate).

B. On-Site Course Responsibilities

_____ 1. Check on and determine final room arrangements (i.e., tables, chairs, lectern, water, cups, etc.).

_____ 2. Set up AV equipment required each day and brief operator (if supplied).

_____ 3. Post signs where needed.

_____ 4. Alert receptionist, phone operator(s), watchmen, etc., of name, location, and schedule of program.

_____ 5. Conduct a new speaker(s) (i.e., instructor) briefing session on a daily basis.

_____ 6. Verify and make final food services/coffee arrangements (where appropriate).

_____ 7. Identify and arrange for other physical needs as required (i.e., coat racks, ashtrays, etc.).

_____ 8. Make a final check on arrival of guest speakers (instructors) for the day.

C. Post-course Responsibilities

_____ 1. Request honorarium and expense statements from faculty; order and process checks.

_____ 2. Write thank-you letters and send checks to paid faculty.

_____ 3. Write thank-you letters to non-paid guest speakers and others who may have contributed to the success of the course.

_____ 4. Prepare evaluation on each course (including instructions, content, facilities, etc.).

_____ 5. Make sure AV equipment is returned.

_____ 6. Return unused materials to your office.

COURSE 413

CONTROL OF PARTICULATE EMISSIONS

COURSE GOAL

Upon completion of the course, the student will be able to make decisions about the suitability of particulate emissions control systems in terms of their availability to meet emission control regulations. In order to be able to make the required decisions about control systems, the student must learn the principles of equipment operation, control efficiency parameters, typical equipment cost information and typical industrial applications of control equipment. Equipment design will be used as an instructional tool to teach the principles and mechanisms of equipment operation. Developing proficiency in equipment design per se is not a goal of this course. Developing ability to act on applications for a permit to construct an air pollution source and emission control system, as a governmental official, is a goal of this course.

COURSE OBJECTIVES

The student should be able:

(1) to explain briefly in 3 short paragraphs the origin, effects and basic measurement methods of particulates in the atmosphere.
(2) to use the ideal gas law, laws pertaining to temperature, pressure and volume corrections of gases, and the property of viscosity and Reynolds number in particulate control calculations.
(3) to recall the air pollution control standards and regulations relevant to particulate control and to use them as critieria in the evaluation of particulate control equipment.
(4) to describe the hydrodynamic principles and physical processes occurring in the separation of particulate matter from waste gas streams such as diffusion, impaction, interception, gravity, electrostatic and magnetic forces.
(5) to describe the common methods of particle sizing and to choose the appropriate method in calculating the efficiency of a particular emission control device.
(6) to evaluate the design plans for a particulate control device (including: a. settling chambers, b. cyclones, c. wet collection devices, d. electrostatic precipitators, and e. fabric filters). The student should be able to evaluate the design plans in terms of collection efficiency, problems which may impair efficiency and appropriateness of the control technique for the particular source. Once this assessment is completed, the student should be able to determine whether the particulate control device complies with governmental emission control regualtions.
(7) to compare equipment features such as reliability, efficiency, energy use, capital costs, operation costs, construction materials, corrosion, and space requirements; given several particulate control device options for a specific source.

LESSON OBJECTIVES

Lesson 1 - Review of the Basic Concepts

- Recall the problems involved with nomenclature used in the numerous theoretical calculations for control equipment.
- Define in general terms
    - Temperature
    - Pressure
    - Ideal gas law
    - Reynolds number
    - Molecular weight
    - Gas viscosity

Lesson 2 - Particle Dynamics

- Describe the basic forces of gravity and buoyancy and their relationship on a particle.
- Describe the aerodynamic drag force on a particle in motion and the drag coefficient.
- List the three regimes that a particle flows in and their relationships in calculating the drag force for each regime.
- Describe the Cunningham correction factor for the drag coefficient in the laminar regime.
- Describe an overall equation for motion including gravity, buoyancy, and drag.
- Recognize the equation to calculate the terminal settling velocity for a particle in each regime.
- Determine the proper regime by calculating the factor "K".

Lesson 3 - Particle Sizing - Measurement and Mathematical Methods

- Recognize five methods of measuring the size of a particle and briefly describe their operation.
- List the three most important parameters used to rate a particle sizing device.
- Describe the major advantages and disadvantages of each of the five particle measuring devices.
- Describe the aerodynamic diameter of a particle.
- Recognize three typical mathematical methods dealing with particle size distribution.
- Describe the log-normal distribution and the shape of the curves when plotted on various scales.
- Describe the geometric mean and standard deviation and how they can be calculated for a log-normal distribution.
- Discuss how one can estimate a typical particle size distribution from a proposed new source.
- Discuss how one can obtain the actual sample from a source and the subsequent analysis for particle size distributions for each of the measuring devices.

Lesson 4 - Methods for Reducing Particle Emissions

- List four major ways to eliminate or reduce emissions from an air pollution stationary source.
- List three modifications in the operation of a source to reduce the emissions without the use of air pollution control equipment.
- Recognize the five basic types of control equipment used for control of particulate emissions.
- Describe the forces used in the collection mechanisms of particle collection.

Lesson 5 - Settling Chamber: Principles, Operation and Applications

- Describe the collection mechanisms which cause particles to be collected in a settling chamber.
- List three types of settling chambers.
- Recognize Stokes Law for determining the settling velocity and calculate the settling velocity of a particle in a settling chamber.
- Recognize and use the equation for determining the minimum particle size collected in a settling chamber.
- Calculate the collection efficiency of a settling chamber.
- Describe the process design parameters used in designing settling chambers.

Lesson 6 - Cyclones: Principles, Operation and Applications

- Briefly describe the simple operation of a cyclone for a particle collection and describe how the gas flows in a cyclone.
- Name the two collection mechanisms used for the collection of particles in a cyclone.
- Describe the cut size and critical size of a particle.
- Recognize the formula for cut size and calculate the cut size for a specific cyclone.
- Calculate the pressure drop across a cyclone using the pressure drop equation.
- Calculate the collection efficiency of a cyclone using efficiency curves and particle size distribution data.

Lesson 7 - Electrostatic Precipitator Principles and Operation

- List three structural components of an ESP.
- List three different types of ESP's.
- Identify the three basic functions of an electrostatic precipitator.
- Describe each of the following basic mechanisms of the electrostatic precipitation process:
    - Gas ionization by corona discharge

    - Particle charging
    - Particle migration to the collection electrode
    - Loss of the particle electric charge at the collection electrode
    - Electric wind

- Describe the ESP collection electrode cleaning process.
- Write an equation for ESP efficiency calculations.
- List the advantages of the ESP that make it a desirable control device.

Lesson 8 - ESP: Design and Applications

- Describe factors affecting the operation of an electrostatic precipitator.
    - Particle resistivity
    - Gas stream parameters
    - Gas flow distribution
- Discuss common operating problems of ESP's.
- Describe controls used for the ESP.
- List recommended maintenance and operating procedures for assuring optimum ESP performance.

Lesson 9 - Fabric Filter Principles

- List three collection mechanisms used in fabric filtration.
- List three simple designs for baghouses.
- List four cleaning mechanisms and briefly describe their operation.
- Name two types of fabric filter material construction and the use of different fiber types to guard against failure of fabric materials.
- Define pressure drop and recall the simplified formulas for measurement across the cake and across the fabric.
- Describe the sieving action and the formation of the cake and the role played in terms of collection efficiency.
- Define filtration velocity and air to cloth ratio and their role played in terms of fabric filtration performance.

Lesson 10 - Fabric Filter Applications

- Recall the advantages and disadvantages of using fabric filters for collection of particulates.
- Recall the important design factors that are basic to the design of the control system.
- Recognize the various industries where baghouses can be used to collect particulate emissions.

Lesson 11 - Wet Collector Theory

- List the dominant physical mechanisms involved in wet scrubbing.
- Describe the relative effect of particle size, relative velocity and droplet size on the dimensionless "separation numbers" (target efficiency) for each mechanism.

- Calculate the average droplet size of a gas atomized spray using the Nukiyama-Tanasawa relation.
- Define the terms, "inertial impaction parameter", "penetration", "liquid to gas ratio", "cut diameter", and "transfer on".
- Calculate the collection efficiency for a venturi scrubber using the Johnstone correlation.
- State the "cut-power" rule developed by Calvert and give the assumptions associated with the rule.
- Calculate the penetration associated with a given particle cut diameter and scrubber type using the cut-power rule.

Lesson 12 - Wet Collector Design

- Group the different types of wet scrubbers according to their mechanism of power input.
- Describe the operation of at least 5 of the following types of scrubbers using appropriate diagrams.
  - Plate
  - Gas-atomized spray
  - Centrifugal
  - Baffle
  - Self-induced spray
  - Moving bed
  - Preformed spray
  - Mechanically aided
  - Packed
- Discuss the performance characteristics of at least 4 different types of wet collectors, including pressure drop, liquid to gas ratio and problems associated with the design.

Lesson 13 - Operation and Maintenance of Air Pollution Control Equipment

- Define what an operation/maintenance and inspection program is and list three major reasons why such a program should be implemented.
- Recognize the Illinois Environmental Protection Agency's proposed rule dealing with O/M/I programs.
- List three ways an O/M/I program can be cost effective.
- Describe the basic steps of an O/M/I program for a fabric filter collector and identify the important features of the program.
- Identify two typical inspection reporting forms for fabric filter collectors.

Lesson 14 - Estimating the Cost of Control Equipment

- List the major economic factors to be considered in selecting particulate control equipment.
- Estimate the installation cost/ACFM of some types of control equipment.
- Recall generalized formulas for estimating yearly maintenance costs of various control devices.

SAMPLE AGENDA

Name and address of
agency conducting course

413 - Control of Particulate Emissions

(Dates of course)

Acknowledgement of role of other agencies, if any, in conduct or support of presentation.

Name of course moderator

Course location

DAY & TIME	SUBJECT	SPEAKER
Monday		
8:30 - 9:00	Introduction and Welcome - Registration	
9:00 - 10:00	Pre-test	
10:00 - 10:15	Break	
10:15 - 10:30	Course Overview	
10:30 - 12:00	Review of the Basic Concepts Temp. Pressure, Ideal Gas Law, Conservation Laws	
12:00 - 1:00	Lunch	
1:00 - 2:00	Particle Dynamics	
2:00 - 2:30	Particle Dynamics, Problem Session I	
2:30 - 2:45	Break	
2:45 - 3:45	Particle Sizing	
3:45 - 4:15	Particle Sizing, Problem Session II	
4:15 - 4:30	Homework Assignment	
HOMEWORK:	Problem 2-3, 413 Student Workbook, p. 5.	
Tuesday		
8:30 - 9:00	Homework Review	
9:00 - 9:30	Methods for Reducing Particulate Emissions	
9:30 - 10:00	Settling Chamber Principles, Operation and Applications	
10:00 - 10:15	Break	

DAY & TIME	SUBJECT	SPEAKER
Tuesday (continued)		
10:15 - 10:30	Settling Chamber, Problem Session III	
10:30 - 11:15	Cyclone Principles, Operation & Applications	
11:15 - 12:00	Cyclone, Problem Session IV	
12:00 - 1:00	Lunch	
1:00 - 2:15	Electrostatic Precipitator Principles and Operation	
2:15 - 2:30	Break	
2:30 - 3:30	Electrostatic Precipitator Applications	
3:30 - 4:30	Electrostatic Precipitator, Problem Session V	
HOMEWORK:	Problem 5-4, 413 Student Workbook, p. 20.	
Wednesday		
8:30 - 8:45	Homework Review	
8:45 - 10:15	Fabric Filter Principles	
10:15 - 10:30	Break	
10:30 - 11:00	Fabric Filter Applications	
11:00 - 12:00	Fabric Filter, Problem Session VI	
12:00 - 1:00	Lunch	
1:00 - 2:15	Wet Collector Theory	
2:15 - 2:30	Break	
2:30 - 3:30	Wet Collector, Problem Session VII	
3:30 - 4:30	Wet Collector Design	
HOMEWORK:	Problem 7-4, 413 Student Workbook, p. 29.	
Thursday		
8:30 - 9:00	Homework Review	
9:00 - 10:00	Operation & Maintenance of Air Pollution Control Equipment	
10:00 - 10:15	Break	
10:15 - 11:15	Estimating the Cost of Control Equipment	
11:15 - 12:00	Pre-test Review	
12:00 - 1:00	Lunch	
1:00 - 1:30	Course Overview	
1:30 - 2:30	Post-test	
2:30 - 2:45	Course Evaluation	
2:45	ADJOURN	

COURSE #413

REQUIREMENTS FOR AWARD OF CERTIFICATE OF COURSE COMPLETION AND CONTINUING EDUCATION UNITS

Three (3) Continuing Education Units (CEU's) will be awarded along with certificate to those students who:

- attend a minimum of 95% of all scheduled class sessions
- complete and hand in copies of all homework exercises = 10 points
- achieve average course grade of 70%
  course grade = final exam score + homework points

ALL PRE-TESTS, POST-TESTS, AND QUIZZES IN THIS COURSE ARE INTENDED TO BE OPEN-BOOK. STUDENTS ARE ALLOWED TO USE ANY ADDITIONAL MATERIAL, INCLUDING SCIENTIFIC CALCULATORS. SUGGESTED TIME ALLOTMENTS FOR EACH ARE AS FOLLOWS:

PRE-TEST	60 minutes
FINAL EXAM	60 minutes

COURSE #413 CONTROL OF PARTICULATE EMISSIONS

PRE-TEST

This Pre-Test is designed to measure how much you know about particulate control as you begin Course #413. Your score does not affect your final grade in the course. This exam is intended to be OPEN-BOOK; you may use your books, notes, and scientific calculator. All answers should be indicated on the attached answer sheet. You will have sixty minutes to complete the test.

1. A coal fired power plant sends 2400 ACFM through its electrostatic precipitation. Particle migration velocity is known to be 0.35 feet/second. What is the collection area if the overall unit efficiency is 99.78%

   a. 699.35 ft^2

   b. 669 ft^3

   c. 448 ft^2

   d. 288 ft^2

2. An ESP has a single duct with plates 20 ft. high by 24 ft. wide. Inlet grain loading is 2.82 grains/ft^3 and outlet data shows a dust concentration of 0.333 grains/ft^3. What is the particle migration velocity if the flow rate through the ESP is 4,200 ACFM?

   a. 0.156 ft/sec
   b. 0.328 ft/sec
   c. 0.427 ft/sec
   d. 0.228 ft/sec

3. Which of the following statements does not apply to a description of the corona discharge phenomenon in an electrostatic precipitator?

   a. A high d-c voltage of negative polarity is applied to the corona discharge wire
   b. The voltage is set for maximum power yet below the level of excessive sparkover
   c. Electrical breakdown of the gas surrounding the discharge wire occurrs owing to the action of positive ions striking the discharge wire
   d. The intense electrical field near the discharge wire accelerates electrons

4. Avalanche multiplication describes the action of:

   a. Accelerated positive ions striking the discharge wire and producing free electrons by secondary emissions
   b. Corona discharge starting voltage
   c. Accelerated electrons ionizing gas molecules by freeing a valence electron
   d. Current density gradient between the discharge electrode and collection electrode

5. Particles subjected to the electric field and ion bombardment in the area near the corona discharge will migrate toward the collection electrode when they reach:

   a. The proper dielectric constant
   b. Saturation charge
   c. Field charge
   d. Diffusion charge

6. Dust particles with resistivity below 10^4 ohm-cm are difficult to collect:

   a. They rapidly lose their negative charge at the collection electrode but they can acquire a strong positive charge and spring off the plate.
   b. They act as a resistor in series and lower corona current density
   c. They may experience electrical breakdown and produce back corona
   d. They do not readily dissipate negative charge and cling to the collection electrode. They eventually effects the potential difference between electrodes causing intense sparkover

7. Gas conditioning radically effects particle resistivity. The most common conditioning agents are:

   a. Steam and low resistivity particles
   b. Steam and as much as 200 ppm H_2SO_4
   c. Steam and as much as 20 ppm HNO_3
   d. Steam and as little as 20 ppm NH_3 or SO_3

8. The ESP has very low draft losses. A designer may assure proper gas flow into the machine by which of the following?

   a. Gas turning vanes in the duct elbows
   b. Gas turning vanes and an expansion section
   c. Turning vanes at duct elbows, an expansion section, and diffusion screens
   d. Smaller induced draft fans

9. Electrical sectionalization improves ESP efficiency for which of the following reasons?

   a. It assures proper spark rate in all sections of the machine
   b. Eliminates problems with strong space charge lowering current density in sections near the ESP outlet
   c. Maintains optimum voltage and current density in all sections
   d. Both a and c

10. The aspect ratio of a ESP is important for maintaining desired efficiency for the machine. It is defined as:

    a. Ratio of the length to the width for collection plates
    b. Ratio of the collection plate height to the length
    c. Ratio of the primary power input to collection efficiency
    d. Ratio of the inlet dust concentration to collection plate area

11. An inspector in Emit, N. C. examined the control panel of an ESP installed at a steam generator. The primary voltmeter indicated abnormally low voltage. The primary ammeter showed cycling current in the machines. What do you think was the problem with the ESP?

    a. Broken wire swinging in a bus section
    b. Open transformer
    c. Faulty rectifier
    d. High dust level in the hoppers

12. An ESP has very low internal power requirements owing to the fact that it:

    a. Ionizes incoming gas reducing the total mass that must be cleaned
    b. Applies forces as much as 3000 times the force of gravity directly to particles suspended in a gas stream
    c. Corona starting voltage is easily achieved with modern discharge wire designs
    d. Most steam generators have an abundance of cheap power for gas cleaning operations

13. A plant wants to install a cyclone to collect particles from a grinding operation. If the gas viscosity is 1.34×10^{-6} lb/ft-sec and the inlet grain loading is 3 grains/ft^3, what is the cut size of the particle?

Cyclone inlet width	3 ft.
Effective number of turns	5
Inlet gas velocity	40 ft/sec
Specific gravity of the particle	2.9
Density of water	62.4

a. 1.59×10^{-10} ft.
b. 1.59×10^{-5} ft.
c. 9.9×10^{-5} ft.
d. 1.26×10^{-5} ft.

14. The true test of a log normal distribution is:

a. The data plots out as a straight line on semi log paper
b. The area under the curve represents different mass concentrations between d_p and d_p max.
c. The data plots out as a straight line on log probability paper
d. The data plots out bell shaped on log probability paper

15. Industries contemplating the purchase of a wet scrubber system, will most often obtain an estimated value of the pressure drop by:

a. using the cut-power rule
b. guessing
c. using data from a pilot plant
d. using the cut power theory
e. using the Johnstone equation

16. The smallest particle size collected at 100% efficiency by a cyclone is the:

a. cut size
b. geometric size
c. critical size
d. aerodynamic mean size

17. Theoretically, each stage of a cascade impactor would have a particle diameter cut point which is:

    a. 100% efficient
    b. 50% efficient
    c. 84% efficient
    d. 15.87% efficient

18. A 72.7 μm diameter particle moving at it's terminal settling velocity has a drag coefficient in 70°F air determined to be 12 for the Stokes Law regime and 12 for the transition regime. What is the Reynolds number?

    a. 18.5
    b. 2
    c. 500
    d. 24

19. At some point during its acceleration in a force field, a 500 μm particle, suspended in a fluid with viscosity $\mu=1.23 \times 10^{-5}$, and density $\rho=0.075$ lb/ft^3 is characterized by $aC_D=0.44$ calculated with a transition regime equation. The Reynolds number corresponds to the dividing point between the transition regime and Newton's regime. What is the particle velocity?

    a. 50 ft/sec
    b. 40 ft/sec
    c. 100 ft/sec
    d. 2.19 ft/sec

20. The cut-power rule assumes that penetration is equal to:

    a. $\ell n \frac{1}{1-\eta}$
    b. $\exp(-A\ dpa^B)$
    c. $\sqrt{\rho_p c l}\ d_p$
    d. $P_g + P_L$

21. Contact Power Theory states that:

    a. As pressure drop increases, efficiency increases
    b. As pressure drop decreases, efficiency increases
    c. Complexity of design increases efficiency
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22. What would be a fast way to check the efficiency of an operating wet scrubber?

    a. Compare its operation to that of a pilot unit
    b. Do a particle size analysis at the inlet and outlet
    c. Use an empirical formulation along with the operating data
    d. Use a basic theoretical formulation such as the Johnstone formula

23. At absolute zero a gas has:

- a. A temperature of -273.16°C
- b. No kinetic energy
- c. No pressure
- d. All of the above

24. The primary quantities measured in an absolute dimensional system are:

- a. Mass, length, force
- b. Force, length, time, and mass
- c. Mass, length, and time
- d. Force, length, and time

25. Absolute pressure when measured at an elevation above sea level is:

- a. Measured above a perfect vacuum
- b. 29.92 in Hg
- c. Required for proper gage pressure readings
- d. Pabs = Patm. + Pg

26. If a settling chamber is 20 feet wide, 15 feet high, and 30 feet long, and the gas flow rate is 25 ft^3/sec. Calculate the smallest particle droplet (spherical in shape) that will be entirely collected by the settler. The specific gravity of the particle is 1.5 and the viscosity is $1.24 \times 10^{-5} \frac{lb}{ft\text{-}sec}$. Assume Stokes law applies

- a. 5.39×10^{-5} ft
- b. 1.81×10^{-7} ft
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27. Settling chambers are generally used as a pre cleaner to another type of control equipment. As a general rule of thumb, the through put velocity should be:

- a. at least 50 ft/sec
- b. below 10 ft/sec
- c. greater than the pick up velocity
- d. less than 1 inch H_2O

28. The collection mechanisms responsible for approximately 99% of the filtering in a Fabric Filtration system are:

a. diffusion and centrifugal
b. impaction and interception
c. electrostatic attraction
d. agglomeration and direct interception

29. Bags are cleaned in a baghouse that utilizes a shaking motion by:

a. rapping with a hammer and anvil set-up
b. electrifying the bag cage
c. sonic horns, oscillating motion, or vertical motion
d. rinsing the bags with water

30. Reverse air is a type of cleaning mechanism to clean the bag by:

a. reversing the air, causing the bag to collapse
b. causing the bag to vibrate, releasing the dust
c. blowing a jet of aircausing the bag to bubble and release the dust
d. pressurizing the bag

31. Natural fibers used for bags in a baghouse such as cotton and wool have

a. ability to be used for a power plant particle collector
b. a low temperature limitation
c. are very expensive to purchase
d. good resistance to fluoride

32. A fiber that has very good resistance to acidic and alkaline attack and has a high temperature limitation is

a. cotton
b. Teflon
c. fiberglass
d. wool

33. The pressure drop across the baghouse can be calculated by

a. $\Delta p = \Delta P_{Filter} + \Delta P_{cake}$

b. $\Delta p = Q \div A$

c. $\Delta p = (K_3 - 1) \div K_3$

d. $\Delta p = S/v_t$

34. When using a woven material for a bag in a baghouse the efficiency will be low before

a. high pressure drops occur
b. the open spaces in the weave are bridged and the cake is formed
c. an air to cloth ratio 16 to 1 is reached
d. the temperature in the baghouse reaches 300°F

35. In a baghouse a cage for the bag is used in a pressure jet or pulse jet unit to:

a. help the bags collapse
b. help the bag shake
c. support the bag
d. keep the squirrels out

36. Typical units describing the air to cloth ratio are:

a. cfm/ft-min
b. $\mathrm{cfm/ft^2}$
c. $\mathrm{ft^3/ft^2}$
d. cfm/ft

37. A plant has an inlet loading into a baghouse of 10 $\mathrm{grains/ft^3}$. The average filtration velocity is 10 ft/min and the gas flow rate is 25,000 ACFM. What is the air to cloth ratio of the system?

a. 250 ft/min
b. 10 $\mathrm{cfm/ft^2}$
c. 2500 $\mathrm{ft^2/min}$
d. 5 ft/min

38. If a plant has a volumetric flow rate of 18,000 ACFM and a dust loading of 2 $\mathrm{lb/ft^3}$ of gas filtered, how much filtering area would be required if the filtration velocity is 2.5 ft/min?

a. 45,000 $\mathrm{ft^2}$
b. 36,000 $\mathrm{ft^2}$
c. 7200 $\mathrm{ft^2}$
d. 9000 $\mathrm{ft^2}$

39. How many cylindrical bags, 6 inches in diameter and 25 feet long would be needed to filter a particulate laden gas stream; the total filtering surface area is 4045 square feet.

a. 300
b. 162
c. 15
d. 103

40. The geometric standard deviation is calculated for a log normal distribution by dividing

   a. 50% size
   b. 50% size/84.13% size
   c. 15.87 size/2.28% size
   d. dp max/Δlog dp max

41. The geometric mean particle diameter occurs at:

   a. 15.87% fraction
   b. 50% fraction
   c. 84.13% fraction
   d. 97.72% fraction

42. In a cyclone, the cut size of a particle is the size of the particle

   a. collected with 100% efficiency
   b. less than 20 microns
   c. collected with 50% efficiency
   d. which will not be collected

43. In a cyclone the eddie currents can be eliminated by use of

   a. vortex arrestor
   b. outer vortex
   c. eductor
   d. dust hopper

44. In a cyclone the inlet gas velocity is transformed into a vortex which is confined within the structure. The particles are collected when

   a. the particles are thrown against the wall by centrifugal force and fall into the dust hopper
   b. the spiral of the vortex changes direction
   c. Drag force is greater than the centrifugal force
   d. vortex finder corrects with the vortex arrestor

45. The energy used to contact particulates with liquid in an impingement plate scrubber is supplied by

   a. the gas stream
   b. the liquid stream
   c. a mechanically driven motor
   d. a thin film

46. An example of a high energy scrubber would be

   a. a countercurrent spray tower
   b. a turbulent contact absorber
   c. a centrifugal scrubber
   d. a venturi scrubber

47. What would be a characteristic pressure drop for a medium energy scrubber such as a self-induced spray scubber (impingement-entrainment scrubber?

a. 1" H_2O

b. 5" H_2O

c. 20" H_2O

d. 100" H_2O

48. The Nukiyama-Tanasawa relationship is used to estimate

a. particle size
b. liquid to gas ratio
c. water droplet size
d. the relative velocity of particulate matter to water droplets

49. Which one of the methods give below uses the transfer number $N_t = \ln\left(\frac{1}{1-\eta}\right)$ to estimate scrubber collection efficiency?

a. the cut-power rule
b. the Johnstone equation
c. The Nukiyama-Tanasama correlation
d. the contact-power theory

50. What is the most common collection mechanism employed in wet scrubbers?

a. inertial impaction
b. direct interception
c. Brownian diffusion
d. gravitation

Name______________________________

COURSE #413 CONTROL OF PARTICULATE EMISSIONS

PRE-TEST

ANSWER SHEET

1. a b c d
2. a b c d
3. a b c d
4. a b c d
5. a b c d
6. a b c d
7. a b c d
8. a b c d
9. a b c d
10. a b c d
11. a b c d
12. a b c d
13. a b c d
14. a b c d
15. a b c d e
16. a b c d
17. a b c d
18. a b c d
19. a b c d
20. a b c d
21. a b c d
22. a b c d
23. a b c d
24. a b c d
25. a b c d
26. a b c d
27. a b c d
28. a b c d
29. a b c d
30. a b c d
31. a b c d
32. a b c d
33. a b c d
34. a b c d
35. a b c d
36. a b c d
37. a b c d
38. a b c d
39. a b c d
40. a b c d
41. a b c d
42. a b c d
43. a b c d
44. a b c d
45. a b c d
46. a b c d
47. a b c d
48. a b c d
49. a b c d
50. a b c d

COURSE #413 CONTROL OF PARTICULATE EMISSIONS

PRE-TEST

ANSWER KEY

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- b. Force, length, time, and mass
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- a. Measured above a perfect vacuum
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   b. electrifying the bag cage
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   d. pressurizing the bag

31. Natural fibers used for bags in a baghouse such as cotton and wool have

   a. ability to be used for a power plant particle collector
   [✓ b.] a low temperature limitation
   c. are very expensive to purchase
   d. good resistance to fluoride

32. A fiber that has very good resistance to acidic and alkaline attack and has a high temperature limitation is

   a. cotton
   [✓ b.] Teflon
   c. fiberglass
   d. wool

33. The pressure drop across the baghouse can be calculated by

   [✓ a.] $\Delta p = \Delta P_{Filter} + \Delta P_{cake}$
   b. $\Delta p = Q \div A$
   c. $\Delta p = (K_3 - 1) \div K_3$
   d. $\Delta p = S/v_t$

34. When using a woven material for a bag in a baghouse the efficiency will be low before

a. high pressure drops occur
[✓ b.] the open spaces in the weave are bridged and the cake is formed
c. an air to cloth ratio 16 to 1 is reached
d. the temperature in the baghouse reaches 300°F

35. In a baghouse a cage for the bag is used in a pressure jet or pulse jet unit to:

a. help the bags collapse
b. help the bag shake
[✓ c.] support the bag
d. keep the squirrels out

36. Typical units describing the air to cloth ratio are:

a. cfm/ft-min
[✓ b.] cfm/ft^2
c. ft^3/ft^2
d. cfm/ft

37. A plant has an inlet loading into a baghouse of 10 grains/ft^3. The average filtration velocity is 10 ft/min and the gas flow rate is 25,000 ACFM. What is the air to cloth ratio of the system?

a. 250 ft/min
[✓ b.] 10 cfm/ft^2
c. 2500 ft^2/min
d. 5 ft/min

38. If a plant has a volumetric flow rate of 18,000 ACFM and a dust loading of 2 lb/ft^3 of gas filtered, how much filtering area would be required if the filtration velocity is 2.5 ft/min?

a. 45,000 ft^2
b. 36,000 ft^2
[✓ c.] 7200 ft^2
d. 9000 ft^2

39. How many cylindrical bags, 6 inches in diameter and 25 feet long would be needed to filter a particulate laden gas stream; the total filtering surface area is 4045 square feet.

a. 300
b. 162
c. 15
[✓ d.] 103

40. The geometric standard deviation is calculated for a log normal distribution by dividing

a. 50% size
[✓ b.] 50% size/84.13% size
c. 15.87 size/2.28% size
d. dp max/Δlog dp max

41. The geometric mean particle diameter occurs at:

a. 15.87% fraction
[✓ b.] 50% fraction
c. 84.13% fraction
d. 97.72% fraction

42. In a cyclone, the cut size of a particle is the size of the particle

a. collected with 100% efficiency
b. less than 20 microns
[✓ c.] collected with 50% efficiency
d. which will not be collected

43. In a cyclone the eddie currents can be eliminated by use of

a. vortex arrestor
b. outer vortex
[✓ c.] eductor
d. dust hopper

44. In a cyclone the inlet gas velocity is transformed into a vortex which is confined within the structure. The particles are collected when

[✓ a.] the particles are thrown against the wall by centrifugal force and fall into the dust hopper
b. the spiral of the vortex changes direction
c. Drag force is greater than the centrifugal force
d. vortex finder corrects with the vortex arrestor

45. The energy used to contact particulates with liquid in an impingement plate scrubber is supplied by

[✓ a.] the gas stream
b. the liquid stream
c. a mechanically driven motor
d. a thin film

46. An example of a high energy scrubber would be

a. a countercurrent spray tower
b. a turbulent contact absorber
c. a centrifugal scrubber
[✓ d.] a venturi scrubber

47. What would be a characteristic pressure drop for a medium energy scrubber such as a self-induced spray scubber (impingement-entrainment scrubber?

a. 1" H_2O

[✓ b.] 5" H_2O

c. 20" H_2O

d. 100" H_2O

48. The Nukiyama-Tanasawa relationship is used to estimate

a. particle size
b. liquid to gas ratio
[✓ c.] water droplet size
d. the relative velocity of particulate matter to water droplets

49. Which one of the methods give below uses the transfer number $N_t = \ell n\left(\frac{1}{1-\eta}\right)$ to estimate scrubber collection efficiency?

a. the cut-power rule
b. the Johnstone equation
c. The Nukiyama-Tanasama correlation
[✓ d.] the contact-power theory

50. What is the most common collection mechanism employed in wet scrubbers?

[✓ a.] inertial impaction
b. direct interception
c. Brownian diffusion
d. gravitation

Name GRADING KEY

COURSE #413 CONTROL OF PARTICULATE EMISSIONS

PRE-TEST

All questions are 2 Points

ANSWER SHEET

1. [✓ a] b c d
2. [✓ a] b c d
3. a b [✓ c] d
4. a b [✓ c] d
5. a [✓ b] c d
6. [✓ a] b c d
7. a b c [✓ d]
8. a b [✓ c] d
9. a b c [✓ d]
10. a [✓ b] c d
11. [✓ a] b c d
12. a [✓ b] c d
13. a b c [✓ d]
14. a b [✓ c] d
15. a b [✓ c] d e
16. a b [✓ c] d
17. [✓ a] b c d
18. a [✓ b] c d
19. [✓ a] b c d
20. a [✓ b] c d
21. [✓ a] b c d
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37. a [✓ b] c d
38. a b [✓ c] d
39. a b c [✓ d]
40. a [✓ b] c d
41. a [✓ b] c d
42. a b [✓ c] d
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50. [✓ a] b c d

3/20/80

COURSE #413 CONTROL OF PARTICULATE EMISSIONS

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6. The larger the mean particle size of a dust through a cyclone, the higher the value of the:

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   b. inlet velocity
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7. In an electrostatic precipitator the migration velocity is 0.5 ft/sec and the plate area is 10,000 sq. ft. The efficiency of the precipitator is 95.5%. What was the flow rate through the precipitation?

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   b. 65,000 cfm
   c. 1,100 cfs
   d. 1,600 cfs

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   a. $E = 1 - e^{-z}$
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- b. cut-power theory
- c. the Johnstone equation
- d. Nukiyama-Tanasawa relationship
- e. none of the above

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- a. 225.6 ml
- b. 258.6
- c. 100 ml
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- b. 90-100 inches of water
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b. $V = \frac{K}{P}$ at constant T

c. $P = K\ T$ at constant V

d. $pV = \frac{m}{M} RT$

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a. correct the stack gas to standard conditions
b. correct the drag coefficient for fluid flow in the laminar regime
c. determine the settling velocity of a particle in the turbulent regime
d. determine the aerodynamic drag force on a particle

22. A major advantage in using an electrostatic precipitator is that the force for collection is

a. impaction on the collection plate with good collection efficiency
b. centrifugal and gravity to fall into the hopper
c. electrical force with subsequent interception on the discharge electrode
d. applied only to the particle enabling low pressure drops through the collector

23. When collecting particle size data using an in-stack inertial impactor, the size of the particle data collected is given as the:

a. aerodynamic diameter of the particle
b. geometric diameter of the particle
c. Martin's diameter
d. extended area of the particle

24. In a self-induced spray scrubber

a. liquid is injected as high pressure
b. the gas atomizes the liquid
c. particulate matter is removed by cyclonic deposition on the packing
d. gas flow is counter-current

25. Particles collected at the collection electrode of an electrostatic precipitator are usually removed by

a. reversing the flow of air in the collector
b. rapping the electrode by mechanical or electrical mechanism
c. reversing the charge of collection plate
d. creating a vacuum and pulling dust into the hopper

26. In the contact power and cut-power rule, penetration is defined as:

a. $1 - \eta$ (where η = efficiency)
b. C_i/C_o (inlet particle concentration/outlet particle concentration)
c. equal to the total pressure loss, P_T
d. being a constant equal to 2.0 for most inertial wet scrubbers

27. Which of the following is not an integral component in an electrostatic precipitator?

a. rappers
b. collection plate
c. discharge electrode
d. venturi control rod

28. The settling velocity of a particle collected in a settling chamber can be determined by the following formula:

a. $v = \frac{(Re\#)\mu}{d\ell}$

b. $v = \frac{g\, d_p^2 (\rho_p - \rho)}{18\mu}$

c. $v = \frac{L}{H}$

d. $v = \frac{dv}{dt}$ ma

29. A common liquid to gas ratio for a preformed spray scrubber would be

a. 5-20 gal/1000 ft^3
b. .01-.5 gal/1000 ft^3
c. 50-70 gal/1000 ft^3
d. >80 gal/1000 ft^3

30. A Raschig ring would be used

a. around the throat of a venturi scrubber
b. in a cyclonic separator before the pad demister
c. at the top of a cyclonic spray scrubber
d. in a crossflow packed scrubber

31. A log-normal distribution plot is a straight line on:

a. arithmetic graph paper
b. semi-log paper
c. log-probability paper
d. log-log paper

32. Particles are charged in an ESP by

a. subjecting the particles to high humidity
b. corona produced by the discharge electrode when a high voltage is applied
c. positive corona generated by the collection electrode
d. intense electrical field by applying a-c voltage to discharge wire

33. The geometric standard deviation of a log-normal distribution:

a. is the average particle diameter of the distribution
b. can be obtained directly from a plot of particle size versus cumulative percent greater than, on log-probability paper
c. is the 50% size on the log-probability paper
d. given as the 84.13% size divided by the 15.87% size

34. A dominant mechanism in the wet collection of particulate matter is:

a. gravitational force
b. electrostatic force
c. inertial impaction
d. direct interception

35. The migration velocity for a typical design for an ESP is described as

a. effective drift speed of the particle towards the collection electrode
b. being dependent on back corona and spark over
c. being independent of the particle size
d. speed in which the rappers must be activated

36. Particles in a gas stream with high resistivity will

a. migrate to collection electrode and take on the charge of the plate
b. rapidly lose a negative charge
c. readily accept the charge from the discharge wire
d. cause electrical breakdown and spark over

37. Contact power theory is based on the observation that:

a. collection efficiency increases as pressure drop increases
b. condensation of water on particulate matter increases particle size
c. penetration is an exponential function of the cut diameter
d. pilot system parameters may be scaled to larger units

38. In pulse-jet baghouses the cleaning mechanism used for cleaning the bags is:

a. reversing the flow of air through the compartment
b. blast of air into each bag knocking the dust away from the bag
c. blast of air to the outside of the bag
d. pulsating air causing the bags to shake

39. Proper air-to-cloth ratio is

a. the measure of amount of dust deposited on the filter
b. imperative for good design and prevention of premature bag failure
c. often referred to as low filter drag
d. is less than 8 inches of water

40. Ingot Iron and Steel Company has submitted particle size data for dust from their basic oxygen furnace. The data was collected using a Bahco microparticle classifier. The instrument:

a. measures the geometric diameter of the particle collected with an EPA Method 5 sampling train
b. measures particle size by passing the particle through a light beam
c. measures the particle's mobility due to its charge
d. uses a combination of elutriation and centrifugation to separate particles from a weighted sample yielding subsequent particle size data

41. The sieving action plays an important role in

a. measurement of pressure drop across a felted filter
b. eliminating the need for woven fabrics
c. designing multi-compartment baghouses
d. collecting large particles to build the cake for subsequent collection of small particles

42. In a venturi scrubber, efficiency increases when the relative gas to liquid velocity

a. fluctuates
b. decreases
c. increases
d. stabilizes

43. An advantage of using felted material for bag construction in a baghouse is:

a. that larger air-to-cloth ratios are possible
b. they provide lower pressure drops
c. they take longer for the cake to form
d. resistant to acidic gas streams

44. Using contact power theory, estimate the total pressure loss in the system if the pressure drop is 5" H_2O and the liquid to gas ratio is 15 gal/1000 ft^3, with a liquid inlet pressure of 1000psi.

a. 8750
b. 1005
c. 8.75
d. 9.53

45. The pressure drop across a baghouse for shaker or reverse air cleaning type baghouses is:

a. pressure drop across the cake
b. pressure drop across the shell
c. pressure drop across the cake plus the filter
d. inlet pressure plus the outlet pressure

46. Filter drag for fabric filters is a function of

a. quantity of dust accumulated on the filter
b. resistance to air from the filter
c. zone of cake repair
d. force opposing filtration

47. What is the efficiency of a wet scrubber if the overall penetration was found to be .02 by the cut-power theory?

a. 20%
b. 98%
c. 2%
d. 99%

48. The specific collecting area for an Electrostatic Precipitator is given by

a. the electrical wind
b. migration velocity
c. resistivity of the particle
d. A/Q, area divided by the gas volume

49. The dust from a cement kiln is sent to an electrostatic precipitator at 1,600 cfm. The particle migration velocity was measured to be .25 ft/sec. What is the collection efficiency if the collection area is 8000 sq. ft.?

a. 95.8%
b. 95.0%
c. 4.8%
d. 98.2%

50. A multicyclone is used in many applications for collecting dust. The efficiency of a multicyclone for particles greater than 10 microns can be as high as

a. 100%
b. 65%
c. 80%
d. 90%

Name ______________________________

COURSE #413 CONTROL OF PARTICULATE EMISSIONS

POST-TEST

ANSWER SHEET

1. a b c d
2. a b c d
3. a b c d
4. a b c d
5. a b c d
6. a b c d
7. a b c d
8. a b c d
9. a b c d
10. a b c d
11. a b c d
12. a b c d
13. a b c d
14. a b c d
15. a b c d
16. a b c d
17. a b c d e
18. a b c d
19. a b c d
20. a b c d
21. a b c d
22. a b c d
23. a b c d
24. a b c d
25. a b c d
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34. a b c d
35. a b c d
36. a b c d
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38. a b c d
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40. a b c d
41. a b c d
42. a b c d
43. a b c d
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45. a b c d
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37. Contact power theory is based on the observation that:

[✓ a.] collection efficiency increases as pressure drop increases
b. condensation of water on particulate matter increases particle size
c. penetration is an exponential function of the cut diameter
d. pilot system parameters may be scaled to larger units

38. In pulse-jet baghouses the cleaning mechanism used for cleaning the bags is:

a. reversing the flow of air through the compartment
[✓ b.] blast of air into each bag knocking the dust away from the bag
c. blast of air to the outside of the bag
d. pulsating air causing the bags to shake

39. Proper air-to-cloth ratio is

a. the measure of amount of dust deposited on the filter
[✓ b.] imperative for good design and prevention of premature bag failure
c. often referred to as low filter drag
d. is less than 8 inches of water

27. Which of the following is not an integral component in an electrostatic precipitator?

a. rappers
b. collection plate
c. discharge electrode
[✓ d.] venturi control rod

28. The settling velocity of a particle collected in a settling chamber can be determined by the following formula:

a. $v = \frac{(Re\#)\mu}{d\ell}$

[✓ b.] $v = \frac{g\, d_p^{\,2}(\rho_p - \rho)}{18\mu}$

c. $v = \frac{L}{H}$

d. $v = \frac{dv}{dt}$ ma

29. A common liquid to gas ratio for a preformed spray scrubber would be

[✓ a.] 5-20 gal/1000 ft^3
b. .01-.5 gal/1000 ft^3
c. 50-70 gal/1000 ft^3
d. >80 gal/1000 ft^3

30. A Raschig ring would be used

a. around the throat of a venturi scrubber
b. in a cyclonic separator before the pad demister
c. at the top of a cyclonic spray scrubber
[✓ d.] in a crossflow packed scrubber

31. A log-normal distribution plot is a straight line on:

a. arithmetic graph paper
b. semi-log paper
[✓ c.] log-probability paper
d. log-log paper

32. Particles are charged in an ESP by

a. subjecting the particles to high humidity
[✓ b.] corona produced by the discharge electrode when a high voltage is applied
c. positive corona generated by the collection electrode
d. intense electrical field by applying a-c voltage to discharge wire

40. Ingot Iron and Steel Company has submitted particle size data for dust from their basic oxygen furnace. The data was collected using a Bahco microparticle classifier. The instrument:

a. measures the geometric diameter of the particle collected with an EPA Method 5 sampling train
b. measures particle size by passing the particle through a light beam
c. measures the particle's mobility due to its charge
[✓ d.] uses a combination of elutriation and centrifugation to separate particles from a weighted sample yielding subsequent particle size data

41. The sieving action plays an important role in

a. measurement of pressure drop across a felted filter
b. eliminating the need for woven fabrics
c. designing multi-compartment baghouses
[✓ d.] collecting large particles to build the cake for subsequent collection of small particles

42. In a venturi scrubber, efficiency increases when the relative gas to liquid velocity

a. fluctuates
b. decreases
[✓ c.] increases
d. stabilizes

43. An advantage of using felted material for bag construction in a baghouse is:

[✓ a.] that larger air-to-cloth ratios are possible
b. they provide lower pressure drops
c. they take longer for the cake to form
d. resistant to acidic gas streams

44. Using contact power theory, estimate the total pressure loss in the system if the pressure drop is 5" H_2O and the liquid to gas ratio is 15 gal/1000 ft^3, with a liquid inlet pressure of 1000psi.

a. 8750
b. 1005
c. 8.75
[✓ d.] 9.53

45. The pressure drop across a baghouse for shaker or reverse air cleaning type baghouses is:

a. pressure drop across the cake
b. pressure drop across the shell
[✓ c.] pressure drop across the cake plus the filter
d. inlet pressure plus the outlet pressure

46. Filter drag for fabric filters is a function of

[✓ a.] quantity of dust accumulated on the filter
b. resistance to air from the filter
c. zone of cake repair
d. force opposing filtration

47. What is the efficiency of a wet scrubber if the overall penetration was found to be .02 by the cut-power theory?

a. 20%
[✓ b.] 98%
c. 2%
d. 99%

48. The specific collecting area of an Electrostatic Precipitator is given by

a. the electrical wind
b. migration velocity
c. resistivity of the particle
[✓ d.] A/Q, area divided by the gas volume

49. The dust from a cement kiln is sent to an electrostatic precipitator at 1,600 cfm. The particle migration velocity was measured to be .25 ft/sec. What is the collection efficiency if the collection area is 8000 sq. ft.?

a. 95.8%
[✓ b.] 95.0%
c. 4.8%
d. 98.2%

50. A multicyclone is used in many applications for collecting dust. The efficiency of a multicyclone for particles greater than 10 microns can be as high as

a. 100%
b. 65%
c. 80%
[✓ d.] 90%

COURSE #413 CONTROL OF PARTICULATE EMISSIONS

POST-TEST

ANSWER SHEET

ALL QUESTIONS ARE 2 POINTS EACH

1. a b [✓ c] d
2. a [✓ b] c d
3. a b [✓ c] d
4. a [✓ b] c d
5. a [✓ b] c d
6. a b c [✓ d]
7. a b c [✓ d]
8. a b c [✓ d]
9. a b c [✓ d]
10. a b c [✓ d]
11. [✓ a] b c d
12. a b [✓ c] d
13. a b c [✓ d]
14. a b [✓ c] d
15. a b c [✓ d]
16. a b [✓ c] d
17. a b c d [✓ e]
18. [✓ a] b c d
19. [✓ a] b c d
20. a b c [✓ d]
21. a [✓ b] c d
22. a b c [✓ d]
23. [✓ a] b c d
24. a [✓ b] c d
25. a [✓ b] c d
26. [✓ a] b c d
27. a b c [✓ d]
28. a [✓ b] c d
29. [✓ a] b c d
30. a b c [✓ d]
31. a b [✓ c] d
32. a [✓ b] c d
33. a [✓ b] c d
34. a b [✓ c] d
35. [✓ a] b c d
36. a b c [✓ d]
37. [✓ a] b c d
38. a [✓ b] c d
39. a [✓ b] c d
40. a b c [✓ d]
41. a b c [✓ d]
42. a b [✓ c] d
43. [✓ a] b c d
44. a b c [✓ d]
45. a b [✓ c] d
46. [✓ a] b c d
47. a [✓ b] c d
48. a b c [✓ d]
49. a [✓ b] c d
50. a b c [✓ d]

LESSON PLAN

TOPIC: WELCOME AND REGISTRATION

COURSE: 413
LESSON TIME: 30 minutes
PREPARED BY: David S. Beachler
DATE: 4/79

LESSON GOAL: Allow students to introduce themselves to the class; determine the actual level of job experience in the class.

LESSON OBJECTIVES: Each student should know:

1. The name of the organization conducting the course; any other contributing organization; the source of the course materials and any similar information.
2. The name of all instructors and their affiliations
3. The name and employer of each student in the class
4. The phone number where a student may receive messages
5. That the requirements for passing the course are:
    a. Completed registration card
    b. 95% attendance - minimum
    c. All homework completed and turned in = 10 points
    d. Achieve course grade of 70%
    e. Course grade = final exam score + homework points
6. That the teaching method in the course is one of problem solving using the basics learned in these lectures.
7. The nature and uses of class materials:
    a. Course 413 Student Workbook
    b. Course 413 Student Manual

    c. Agenda
    d. Selected handouts
    e. Note paper
    f. Registration card
    g. APTI chronological course schedule

7. The location of:
    a. Restrooms
    b. Refreshments
    c. Restaurants
    d. Transportation facilities

8. Address and phone number (919-541-2766) of EPA - APTI
MD-20, Research Triangle Park, NC 27711

SUPPORT MATERIALS:

1. Student materials package
2. Blackboard and chalk

CONTENT OUTLINE

Course: 413
Lecture Title: WELCOME AND REGISTRATION

Page 1 of 2

I. Introduce self and other instructors present; identify others
   - A. Names and affiliation
   - B. Experience
   - C. Areas of expertise of entity conducting the course

II. Explain relationship to the USEPA, Manpower and Technical Information Branch and the Air Pollution Training Institute. (If appropriate)

III. Logistics of the course location
   - A. Message phone number
   - B. Restrooms
   - C. Refreshments and restaurants
   - D. Encourage students to get together and share experiences, etc.
   - E. Transportation

IV. Introductions - Have each student stand and
   - A. Give name, hometown, and employer
   - B. Describe their air pollution experience; what their job involves.
   - C. Explain what they expect to get from the course.

V. Description of teaching methods
   - A. Training
     - 1. Course directed at training students to perform a specific skill
     - 2. Methods used in the course will be explicit not implicit
   - B. Instructors
     - 1. Will be there to help student become trained
     - 2. Will add their experience and expertise to the training
     - 3. Encourage questions; but avoid use of whole class time for individual interests.
   - C. Approach
     - 1. Teach the basic operation and design features of particulate control equipment
     - 2. Teach the fundamental formulas for efficiency, Δp, and other design parameters
     - 3. Solve problems by applying these fundamentals

NOTES

Write on Board

Write names on the Board

VI. Course Requirements

- A. Completed registration card
- B. Pre-test
- C. 95% attendance - minimum
- D. All homework completed and turned in
- E. Post-test
- F. Course critique completed and turned in
- G. Homework problems will count as 10 points
- H. Final grade will be post-test score plus homework points; 70% minimum passing grade.

VII. Materials - have students check that they have:

- A. Manual
- B. Workbook
- C. Agenda
- D. Note paper
- E. Registration card
- F. APTI Chronological Course Schedule
- G. Local information sheet (phones, addresses, restaurants etc.)

VIII. Pre-test and registration

- A. Explain that the pre-test
    1. Tests what they know as they enter the course
    2. Does not count in the final course grade
    3. Will be correlated to post-test grade to measure actual learning in the course; to improve course and tests.
    4. Students should not guess at answers
- B. Registration card - completely filled out
- C. Begin the pre-test and tell students to take a break after the test
- D. Collect all tests and registration cards - grade tests promptly and report low, high, and average grades.
- E. Instructor will collect the tests (so as to eliminate an agency from building a test file).

LESSON PLAN

AIR POLLUTION TRAINING INSTITUTE

TOPIC: REVIEW OF THE BASICS

COURSE: 413 - Lesson 1
LESSON TIME: 1 hour
PREPARED BY: David Beachler
DATE: 4/19/79

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

LESSON GOAL: To explain the meaning of numerous symbols and basic concepts that are used when performing particulate emission control calculations.

LESSON OBJECTIVES: At the end of the lesson the student should be able:

* Define in general terms
  - Pressure -- gage, barometric, absolute
  - Temperature -- Centigrade, Farenheit, Kelvin, Rankine
  - Density
  - Ideal Gas Law
  - Molecular weight
  - Gas viscosity
  - Reynolds Number
* Calculate pressure, temperature and volume changes
* Calculate the Reynolds Number

PRE-REQUISITE SKILLS: Engineering or physical science background

LEVEL OF INSTRUCTION: College undergraduate science

INTENDED STUDENT BACKGROUND: College math and science

SUPPORT MATERIALS AND EQUIPMENT:

1. Slide projector
2. Chalkboard
3. Pocket calculator for each student -- or slide rule to do calculations
4. 413 Student Workbook

REFERENCES:

1. 413 Student Manual
2. 413 Student Workbook

AUDIO-VISUAL MATERIALS FOR LESSON 1

Lesson 1 Review of the Basic Physical Constants

413-1-1	Properties of gases
413-1-2	Temperature
413-1-3	Temperature conversion
413-1-4	Temperature conversion
413-1-5	Absolute temperature
413-1-6	Atmospheric pressure
413-1-7	Gauge pressure
413-1-8	Absolute pressure
413-1-9	Density
413-1-10	Specific gravity
413-1-11	Atomic number--oxygen
413-1-12	Atomic weight--oxygen
413-1-13	Molecular weight
413-1-14	Mole--molecular weight
413-1-15	Mole--oxygen
413-1-16	Boyles law
413-1-17	Problem--volume change at constant temperature
413-1-18	Solution--volume change
413-1-19	Charles-Gay Lussac law
413-1-20	Problem--volume change at constant pressure
413-1-21	Solution--volume change
413-1-22	Ideal gas law
413-1-23	Volume of one mole-standard conditions
413-1-24	Viscosity--definition
413-1-25	Viscosity--high, low
413-1-26	Temperature effect on viscosity for liquids
413-1-27	Temperature effect on viscosity of gases
413-1-28	Kinematic viscosity
413-1-29	Reynolds number
413-1-30	Reynolds number range-pipe flow
413-1-31	Review

AIR POLLUTION TRAINING INSTITUTE

CONTENT OUTLINE

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

Course: 413 - Lesson 1
Lecture Title: REVIEW OF THE BASICS

Page 1 *of* 7

NOTES

I. Introduction - fundamentals

Some of the important properties of gases one must consider when working with gaseous emission control equipment include:

- Temperature 413-1-1
- Pressure
- Density
- Molecular weight
- Ideal Gas Law
- Viscosity
- Reynolds Number

A. Temperature

1. Defined as the degree of hotness or coldness measured on a definite scale.
2. The temperature range in Fahrenheit and Celsius scales is based on the freezing and boiling point of water. For F° it is 180 and for C° it is 100. 413-1-2
3. The following relationships convert from one scale to another

   $^{o}F = 1.8\ C^{o} + 32$ 413-1-3
   $^{o}C = (^{o}F - 32)/1.8$ 413-1-4

4. Absolute temperature
   a. Experiments have shown that a perfect gas under constant P, for each change in °F below 32°F - the volume of gas changes 1/491.67
   b. Similarily for each °C, volume changes 1/273
   c. If change in volume per degree is constant, what volume of gas theoretically would become zero at 491.6°F below 32°F or at -460°F. For Centigrade it would be -273°C
   d. Absolute temperatures determined by °F are expressed as °F or Rankine.

      $°R = °F + 460°$ 413-1-5

   e. Absolute temperatures determined by °C are expressed as °K or Kelvin.

      $°K = °C + 273$

B. Gas Pressure

1. Defined as application of force to something else in direct contact with it. Pressure is usually expressed in units of force divided by area.
2. Barometric pressure — pressure measured with a barometer, synomous with atmospheric pressure, usually expressed in inches, mm, of mercury. 413-1-6

(weight exerted by atmospheric air)

Standard barometric pressure is 14.7 lbs/in^2 exerted at a base of a column of mercury 29.9 inches high. Weather and altitude are responsible for barometric pressure changes.

(1 atm or 760 mm Hg Standard Pressure)

3. Guage Pressure -- is measured by a guage and indicates the difference in pressure above or below the atmospheric pressure, (expressed in psig).

413-1-7

   a. If pressure of system > atmospheric pressure then guage pressure is +.
   b. If pressure of system < atmospheric pressure then guage pressure is - (a vacuum)

4. Absolute Pressure -- since guage pressure is the pressure of the system relative to the atmosphere then the algebraic sum of gage pressure plus atmospheric pressure yields

413-1-8

$$P_{ABS} = P_{guage} + P_{atm} \quad \text{(Psia)}$$

C. Density

1. Defined as the mass per unit volume

413-1-9

$$\rho. = \frac{m}{V}$$

2. Units expressed in g/cc, g/liter, lb/ft^3

3. In the case of liquids and solids the temperature at which the density was measured is denoted in the table of physical data (tables in books such as Perry's Chemical Engineer Handbook).

4. Gas densities refer to the density of that particular gas at 0^oC and 1 atmosphere pressure.

5. a. A related concept to density is specific gravity which is defined as the ratio $m/V/m_o/V$ where m and m_o are the true weights of the substance and of water in the same volume.

413-1-10

   b. For gases, specific gravity of a gas is referred to dry air at the same pressure and temperature (instead of water) usually at 32°F, 29.291 in Hg, or 0^oC, 760 mm Hg.

6. An example of specific gravity of a gas He = .1368

Example: do on overhead or blackboard

$$\text{Density} = (\underset{\text{sp. gravity}}{.1368})(1.2928\ \underset{\text{density of air}}{g/1}) = .1769\ g/1$$

7. For gases the specific gravity can be defined as the ratio of the molecular weight of the gas to the molecular weight of air which is 29. i.e.

$$\text{specific gravity He } \frac{4.00}{29} = \underline{\underline{.137}}$$

Note:
$$\text{sp. gr} = \frac{\text{m.w. gas}}{\text{m.w. air}} = \frac{4.00}{29} = .137$$

D. Molecular Weight

1. Atomic number of an element (on the periodic chart) is the number of protons contained in the nucleus.

413-1-11

2. Atomic weight -- is the average isotopic mass. i.e.

8 ← atomic no.
O
atomic wt. → 16

Atomic Mass Units

Note: Mendeleev
(Russian chemist
developed the
periodic chart)

413-1-12

Note AMU

413-1-13

3. Molecular Weight - now is sum of the atomic weight of all the atoms in a molecule. i.e.

oxygen O═══O = 32
16 16

1 molecule of O_2

M.W. = 2(16) = 32 AMU

4. a. Mole or gram mole -- is the amount of a substance that contains as many atoms, molecules or ions as 12 grams of Carbon 12. The number of elementary particles in 12 grams C is 6.02×10^{23}.

413-1-14

b. i.e. 1 mole of oxygen O_2 has 32 g, 1 mole H_2O has 18 g.

413-1-15

NOTE:
mole-gram mole of O_2

c. Each mole or gram-mole contains an Avogadro's number of molecules (atoms or ions), 6.02×10^{23}, and each mole of a gas at standard conditions 0°C and 1 atm pressure occupies 22.4 liters in volume.

E. Ideal Gas Law

1.

a. Boyles' Law -- at a constant temperature, a fixed weight of a particular gas occupies a volume that is inversely proportional to the pressure exerted on it.

413-1-16

$$\frac{P_1}{P_2} = \frac{V_2}{V_1} \qquad P_{initial} \times V_{initial} = P_{final} \times V_{final}$$

$$p \propto \frac{1}{V}$$

b. Example

413-1-17

@ constant temp. the volume of gas measured at 745 mmHg was 200 ml, what is the volume of gas at 760 mmHg?

413-1-18

(1) $P_1V_1 = P_2V_2$

(2) $(745)(200) = (760)(V_2)$

(3) $V_2 = \frac{(745)(200)}{760} = 196$ ml

2\.

a. Charles Law -- states that when the volume is held constant, the absolute pressure of a given mass of an ideal gas of a given composition varies directly as the absolute temperature.

Write on overhead: Charles Law

$$p \propto T$$

$$\frac{P_1}{T_1} = \frac{P_2}{T_2}$$

P_1 = initial pressure
P_2 = final pressure
T_1 = initial temperature
T_2 = final temperature

413-1-19

b. Charles-Gay Lussac Law -- volume is directly proportional to temperature at constant pressure

$$V \propto T \text{ or } \frac{V_1}{T_1} = \frac{V_2}{T_2}$$

413-1-20
413-1-21

c. Example: @ constant pressure, the volume of a gas measured at 20°C was 200 ml. What is the volume at 25°C

$$\frac{200}{293} \times 298 = V_2 = 203 \text{ ml}$$

3. Ideal Gas Law

a. Both Boyles and Charles Law are satisfied by the Ideal Gas Law

$$pV = \frac{mRT}{M}$$

413-1-22
413-1-23

p = absolute pressure of gas
V = volume of gas
m = mass of gas
T = absolute temperature of gas
M = gas molecular weight
R = universal gas constant

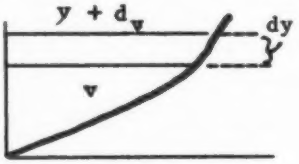
b. It is very important that the value of R is not dimensionless.

c. Values of the universal gas constant R are: — Point out R values

R value	Units
1.987	BTU/(lb.mole)(°R) or Cal/(gram mole)(°K)
0.730	(atm)(ft^3)/(lb.mole)(°R)
10.73	(psia)(ft^3)/(lb/mole)(°R)
82.06	(atm)(cm^3)/(gram mole)(°K)

F. Viscosity

1. Viscosity is a proportionality constant associated with a fluid resistance to flow.
2. Viscosity is the result of two phenomena — 413-1-24
    a. Intermolecular cohesive forces
    b. Momentum transfer between layers of fluid caused by molecular agitation perpendicular to the direction of motion
    c. Point out for liquids -- intermolecular cohesive forces most important — Point out c.
    d. Gases momentum -- transfer most important — Point out d.
3. Between the adjacent layers, a shearing stress occurs which is directly proportional to the velocity gradient



$$g_c T = \mu \frac{dv}{dy}$$

where: T = unit shearing stress between adjacent layers

$\frac{dv}{dy}$ = velocity gradient

μ = proportionality constant — 413-1-25

4. Liquid -- for liquids the momentum between layers is small compared to the cohesive forces between the molecules. Hence T is predominantly a result of intermolecules attraction. Since intermolecular cohesion rapidly decrease with temperature, the shear force decreases with increase in temperature $\because T \alpha \mu$ $\therefore \mu$ decreases with increase in T. — 413-1-26

413-1-27

5. Gases -- In gas, the molecules are too far apart for inter-molecular cohesion to be effective. So the shear stress is predominantly the result of an exchange of momentum between flowing layers caused by molecular activity. Since molecular activity increases with T, T increases with temperature, increasing μ.

Units — one unit used to describe viscosity is the centipoise = 1/100 gm/cm-sec.
English units are obtained by multiplying the value of centipoise by 6.72×10^{-4}. The english units for viscosity are lb_m/ft.sec.

By knowing the temperature of gas, μ can be obtained from a reference book such as "Perry's Chemical Engineer's Handbook".

413-1-28

6. Kinematic viscosity is given by the symbol ν

$$\nu = \mu/\rho$$

where ν = kinematic viscosity
μ = viscosity
ρ = density

413-1-29

G. Reynolds Number

1. The Reynolds Number is a dimensionless quantity frequently encountered in A.P. and characterizes the nature of fluid flow.

Re # is defined as $\dfrac{\text{inertial forces}}{\text{viscous forces}}$ $\qquad Re = \dfrac{vD\rho}{\mu}$

where:
Re = Reynolds Number
D = diameter of duct gas flowing in
v = gas velocity
ρ = gas density
μ = gas viscosity

413-1-30

2. For flow of gases in a circular pipe:
$Re < 2000$ flow is laminar
$Re > 2500$ flow is turbulent

CONTENT OUTLINE

Course: 413 - Lesson 1
Lecture Title: REVIEW OF THE BASICS

Page 7 *of* 7

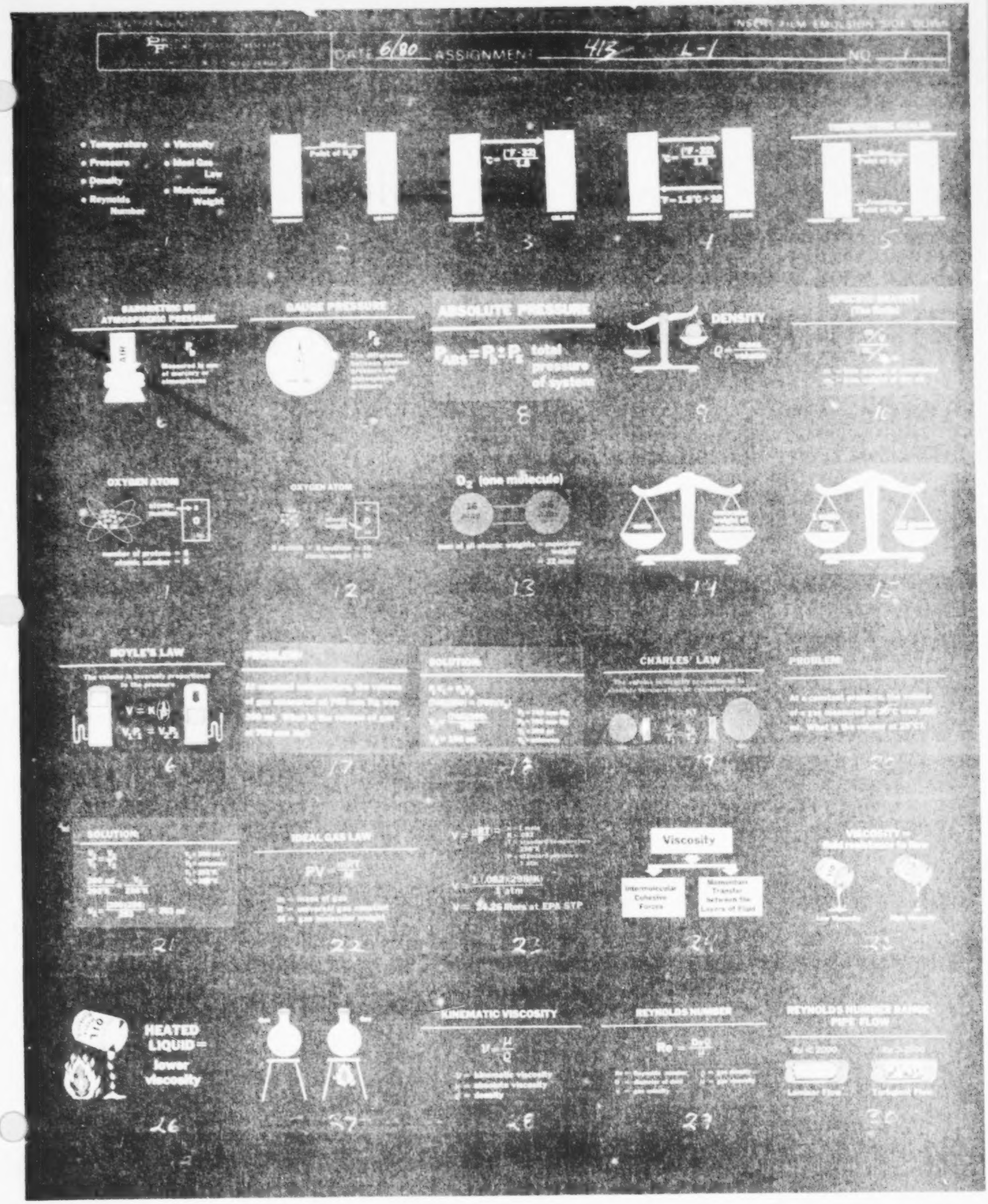
NOTES

II. **Review**

The past hour we've talked about the following concepts:

413-1-31

- **Temperature**
- **Pressure**
- **Density**
- **Ideal Gas Law**
- **Molecular weight**
- **Viscosity**
- **Reynolds Number**



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DATE 6/80 ASSIGNMENT 413 L-1 NO. 1

- Temperature
- Pressure
- Density
- Reynolds Number
- Viscosity
- Ideal Gas Law
- Molecular Weight

1

Boiling Point of H_2O

2

$°C = \frac{(°F-32)}{1.8}$

3

$°C = \frac{(°F-32)}{1.8}$

$°F = 1.8°C + 32$

4

TEMPERATURE SCALES

5

BAROMETRIC OR ATMOSPHERIC PRESSURE

Measured in mm of mercury or atmospheres

6

GAUGE PRESSURE

ABSOLUTE PRESSURE

$P_{ABS} = P_b \pm P_g$ total pressure of system

8

DENSITY

9

SPECIFIC GRAVITY (The Ratio)

10

OXYGEN ATOM

number of protons = 8

atomic number = 8

11

OXYGEN ATOM

12

O_2 (one molecule)

13

14

15

BOYLE'S LAW

The volume is inversely proportional to the pressure

$V = K\left(\frac{1}{P}\right)$

$V_1P_1 = V_2P_2$

16

PROBLEM:

17

SOLUTION:

18

CHARLES' LAW

19

PROBLEM:

20

SOLUTION:

21

IDEAL GAS LAW

$PV = \frac{mRT}{M}$

22

$V = \frac{nRT}{P}$

$V = \frac{1(.082)(298K)}{1\ atm}$

V = 24.26 liters at EPA STP

23

Viscosity

Intermolecular Cohesive Forces

Momentum Transfer between the Layers of Fluid

24

VISCOSITY = fluid resistance to flow

25

HEATED LIQUID = lower viscosity

26

27

KINEMATIC VISCOSITY

$\nu = \frac{\mu}{\rho}$

28

REYNOLDS NUMBER

$Re = \frac{D\nu\rho}{\mu}$

29

REYNOLDS NUMBER RANGE PIPE FLOW

Laminar Flow

Turbulent Flow

30

STYLE NO. 35 70

DATE 6/80 ASSIGNMENT NO. 413 L-1 FILE NO.

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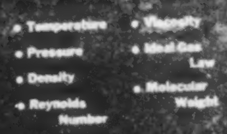
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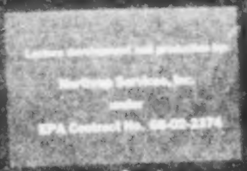
- Pressure
- Density
- Reynolds Number
- Viscosity
- Ideal-Gas Law
- Molecular Weight

31


Lecture development and production by

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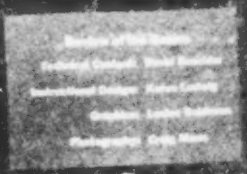
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Instructional Design: [illegible]

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LESSON PLAN

AIR POLLUTION TRAINING INSTITUTE

TOPIC: PARTICLE DYNAMICS

COURSE: 413 - Lesson 2
LESSON TIME: 1 hour
PREPARED BY: DATE: 4/79
David S. Beachler

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

LESSON GOAL: Describe particle behavior in a fluid due to external forces such as gravity, buoyancy and drag force.

LESSON OBJECTIVES: At the end of the lesson, the student should be able to:

- Describe the basic forces of gravity and buoyancy and their relationship to a particle and its motion.
- Describe the aerodynamic drag force on a particle in motion and the drag coefficient.
- List the three regimes that a particle may flow in and their relationships in calculating the drag force for each regime.
- Describe the Cunningham correction factor for the drag coefficient in the Laminar regime.
- Describe an overall equation for motion including gravity, buoyancy, and drag.
- Recognize the equation to calculate the terminal settling velocity for a particle in each regime.
- Determine the proper regime by calculating the factor "K".

STUDENT PREREQUISITE SKILLS:

Ability to understand basic principles of physical science.

LEVEL OF INSTRUCTION:

Advanced

INTENDED STUDENT PROFESSIONAL BACKGROUND:

Engineering or Physical Science

SUPPORT MATERIALS AND EQUIPMENT:

1. Slide Projector
2. Overhead Projector
3. Chalkboard
4. 413 Student Manual

REFERENCES:

1. 413 Student Manual
2. 413 Student Workbook pp. 1-2
3. "Fluid Mechanics", Victor L. Streeter, and E. Benjamin Wylie, sixth edition, McGraw-Hill Book Company, New York, 1975, pp 1-710.
4. Lecture notes prepared by Cliff I. Davidson, Carnegie Mellon University, March 1, 1979.

AUDIO-VISUAL MATERIALS FOR LESSON 2

Lesson 2 Particle Dynamics

413-2-1	Particle force
413-2-2	Forces applied to a particle
413-2-3	Gravity--equation
413-2-4	Buoyancy--equation
413-2-5	Buoyant force
413-2-6	Aerodynamic drag force
413-2-7	Aerodynamic drag force--equation
413-2-8	Drag coefficient
413-2-9	Reynolds number
413-2-10	Flow regimes
413-2-11	Drag coefficient versus Reynolds number
413-2-12	Flow regimes--drag coefficients and Reynolds number
413-2-13	Drag force--transition regime
413-2-14	Drag force--turbulent regime
413-2-15	Laminar regime
413-2-16	Drag coefficient and Cunningham correction factor in laminar regime
413-2-17	Drag force--laminar regime
413-2-18	Terminal settling velocity
413-2-19	Settling velocity--laminar regime
413-2-20	Settling velocity--transition regime
413-2-21	Settling velocity--turbulent regime
413-2-22	Determining the proper regime
413-2-23	Determining the proper K value
413-2-24	Calculating the K value
413-2-25	K values for various regimes
413-2-26	Review--flow regimes
413-2-27	Review
413-2-28	Review

CONTENT OUTLINE

AIR POLLUTION TRAINING INSTITUTE

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

Course: 413 - Lesson 2
Lecture Title: PARTICLE DYNAMICS

Page 1 **of** 9

NOTES

I. Introduction

A. The basic concept that we will be dealing with in this lesson and throughout the course is to describe the mechanisms in which particles are removed from exhaust gases of an emission source.

B. To understand the basics of particulate control technology it is necessary to understand the basic physics behind particle behavior in a fluid, and specifically in a gas stream.

C. The main question is; How can we separate particles from a gas stream by applying external forces?

II. Forces Applied to a Particle in a Fluid 413- 2-1

A. General Equation

1. The force on a particle can be described by:

$$F = m_p a_p$$

where F is the force on the particle in lb_f, m_p is the mass of the particle, and a_p is the acceleration of the particle in ft/sec^2.

2. What are the units of m_p?

$$m_p = \frac{lb_f}{ft/sec^2} = \frac{V_p \rho_p}{g_c}$$

where: V_p = the volume of the particle in ft^3

ρ_p = particle density in $\frac{lb_m}{ft^3}$ (pounds of mass)

g_c = gravitational constant which is given as $\frac{32\ lb_m\ ft/sec^2}{lb_f}$ 413- 2-2

B. Force Due to Gravity

1. Basic equation - We can write an equation for gravity (assume that there are no other forces acting at this time)

$$F_G = W = V_p \rho_p \frac{g}{g_c}$$ 413-2-3

where: W = weight in lb_f

g = local gravitation acceleration ft/sec^2 which is 32.1 in most places in U.S. (except of course in Denver, etc.)

2. We can see that the force due to gravity is dimensionally consistent and given F_G in units lb_f

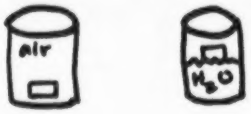
C. Force Due to Buoyancy — 413-2.4

1. The buoyant force (on a particle) is equal to the weight of the displaced fluid and can be given by the equation

$$F_B = V_p \rho \frac{g}{g_c}$$

where ρ = density of the fluid lb m/ft^3
V_p = volume of particle ft^3

2. An example of the buoyant force can be shown by two buckets one filled with air, the other with water. — 413-2.5

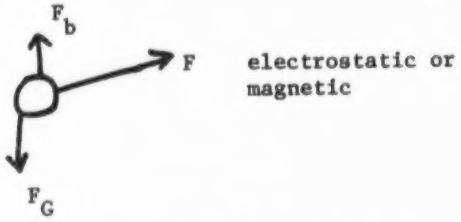


and let's place identical objects in each bucket. Since the ρ air << ρ water then $F_{B(air)} << F_{B(water)}$ and the object rises in water bucket.

III. Aerodynamic Drag Force

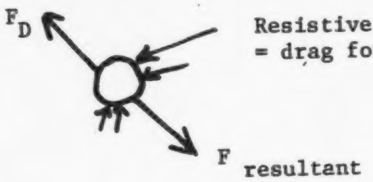
A. Forces on a Particle

1. Let's say there are several forces acting on a particle: — 413-2-6



If the vector sum of these forces is not zero, then the particle will move.

2. Whenever there is particle motion, there will be a resistive force caused by the fluid molecules resisting the motion of the particle.



3. The equation for calculating drag force is given by: 413-2.7

$$F_D = C_D \frac{\rho v^2}{2\ g_c} A_{\text{projected}}$$

($A_{\text{projected}}$ is the area of the particle in direction of flow)

where: $A_{\text{projected}} = \frac{\pi d_p^2}{4}$ for spherical particles of diameter d_p

v = particle velocity relative to the fluid

C_D = drag coefficient

4. C_D is a function of particle velocity, particle diameter, and characteristics of the fluid. But it has been found that C_D is a unique function of a dimensionless combination of these parameters: 413.2.8

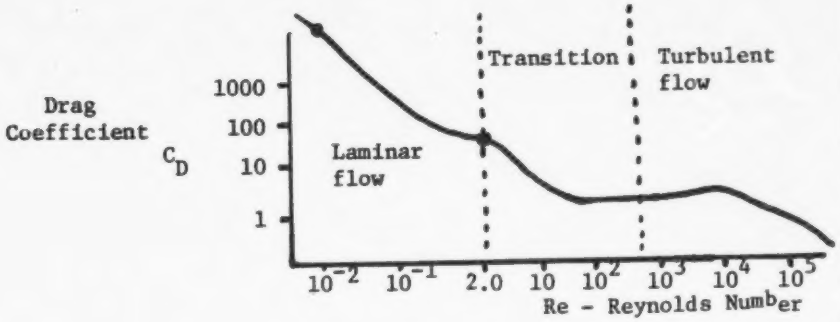
C_D = function of Re (Reynolds Number) 413-1.9

where $Re = \frac{v\ d_p\ \rho}{\mu}$

μ = fluid viscosity
ρ = density of fluid
d_p = particle diameter
v = velocity

5. If we look at a graph of C_D versus Re we can see three regimes

413-2.10



413-2.11

This figure is given in the 413 Manual as Figure 2.2.1 on page 2-16.

6. We can now write the equation for this curve in each region

413-2.12

   a. Laminar, (Re < 2) $C_D = \frac{24}{Re}$

      (Stokes Law)

   b. Transition (2 < Re < 500) $C_D = \frac{18.5}{Re^{.6}}$

   c. Turbulent $(500 < Re < 2 \times 10^5)$ $C_D \simeq 0.44$

      (Newtons regime)

   In general the equation can be written

   $$C_D = a\, Re^{-b}$$

   Where a and b take on different values in each regime.

7. Drag Force Equations

   In order to calculate the drag force on a particle we merely have to substitute the proper C_d expression into the equation for F_D

7. cont'd

$$F_D = \frac{a\, v^{-b}\, d_p^{-b}\, \rho^{-b}}{\mu^{-b}} \quad \frac{\rho v^2}{2g_c} \quad \frac{\pi d_p^{\,2}}{4}$$

substitute for a and b, and simplifying we get

(a) Transition Regime (a = 18.5, b = 0.6) 413-2.13

$$F_D = \frac{18.5\pi}{8}\ \mu^{0.6}\ \rho^{0.4}\ \frac{(v\, d_p)^{1.4}}{g_c}$$

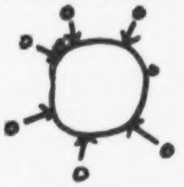
(b) Newtons Regime (a = 0.44, b = 0) 413-2.14

$$F_D = \frac{.44\ \rho}{8}\ \frac{\rho\ (v\, d_p)^2}{g_c}$$

C. Laminar Regime

1. There is a problem when the particle gets very small.

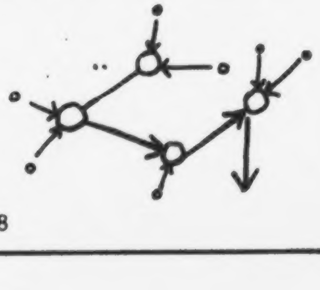
(a) if d_p is much greater than 1 μm the fluid appears continuous and the particle is not affected by collisions with individual air molecules. 413-2.15



(collisions occur very frequently on all sides of the particle)

(b) If the particle is much smaller than 1 μm

Collisions on one side of the particle are more likely to occur. This will cause particle to move in a direction related to the combined forces acting on the particle.



Thus the particle will slip between air molecules (when it is very small) and C_D will reduce to: 413-2.16

$$C_D = \frac{24}{Re\ C_f}$$

Where: C_f is the Cunningham correction factor

2. Now we can write F_D as 413-2.17

$$F_D = \frac{24\pi}{8\ C_f}\ \mu\ \frac{v\ d_p}{g_c}$$

$C_f \gtrsim 1$ for $d_p > 1\ \mu m$

$C_f > 1$ for $d_p < 1\ \mu m$

IV. Equation of particle Motion

A. Forces

We discussed several forces individually so far

F_B (buoyancy)

F_D (drag)

F_G (gravity)

F (external, such as gravity)

Let's combine all of these forces into a single equation and then examine the resultant force.

$$F_R = F_G - F_B - F_D = \frac{m_p}{g_c}\ \frac{dv}{dt}$$

We often define f = force per unit mass of the particle

$$f_R = \frac{dv}{dt} \Big/ g_c = f_G - \underset{\underset{\frac{F_B}{m_p}}{\downarrow}}{\left[\frac{\rho}{\rho_p}\ f_G\right]} - \frac{F_D}{mp}$$

The 413 manual discusses other external forces, such as electrostatic and centrifugal forces. We won't be considering these, but rather let's examine the motion of a particle subjected to the three forces above.

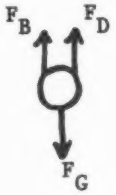
B. Drag Force

If we have a particle which has a greater density than air, (like most particles), then the particle will accelerate according to the equation.

But, what happens to the size of F_D as the particle accelerates?

Remember F_D increases as v increases. Thus there will be some value of v where F_D is as large as the other forces. At that point, the resultant force will be zero and the particle will no longer accelerate.

We can determine the value of v where all forces balance. Called terminal settling velocity. 413-2.18



$F_G - F_B - F_D = 0$ (at terminal settling velocity)

Defining force per unit mass = f

$$f_r = 0 = f_G - \left(\frac{\rho}{\rho_p}\right) f_G - \frac{F_D}{m_p}$$

C. Terminal Settling Velocity

1. Now substitute for F_D from each regime (equations previously given) and solve for terminal settling velocity v.

2. For Stokes Law (Re< 2)

$$f_G - \left(\frac{\rho}{\rho_p}\right) f_G - \frac{F_D}{m_p} = 0$$

$$\frac{g}{g_c}\left(1 - \frac{\rho}{\rho_p}\right) = \frac{F_D}{m_p}$$

$$\frac{g}{g_c}\left(1-\frac{\rho}{\rho_p}\right) = \frac{3\pi}{C_f}\,\mu\,\frac{vd_p}{g_c} \Big/ \frac{\pi}{G}\,d_p^{\,3}\rho_p$$

413-2.19

Solving for v, and defining v as v_t the terminal settling velocity, we obtain

$$v_t = \frac{g\,d_p^{\,2}\,(\rho_p-\rho)\,C_f}{18\mu}$$

3. For the Transition Regime

413-2.20

$$v_t = .153\,g^{0.71}\,d_p^{\,1.14}\,\rho_p^{\,0.71} \Big/ \mu^{0.43}\,\rho^{0.29}$$

4. For the Newton's Regime

413-2.21

$$v_t = 1.74\,(g\,d_p\,\rho_p/\rho)^{0.5}$$

D. Determining the Proper Regime

413-2.22

1. It is necessary to determine which regime is correct for the particle when one is attempting to calculate the settling velocity.

413-2.23

2. One can't just solve for Re, and determine the regime, since you need to know the velocity to calculate the Re, yet you're trying to solve for v.

3. In the 413 Manual, the author explains that one can calculate a new parameter K

413-2.24

where: $K = d_p\left[g\,\rho_p\,\rho/\mu^2\right]^{1/3}$

when: $K < 3.3$ we're in Stokes Law Regime

$3.3 < K < 43.6$ we're in Transition Regime

$K > 43.6$ we're in Newton's Regime

4. Once we determine the proper regime (by calculating K) we then know which equation to use for calculating drag force and settling velocity.

413-2.25

CONTENT OUTLINE

NOTES

Course: 413- Lesson 2
Lecture Title: PARTICLE DYNAMICS

V. REVIEW - Handout Lecture outline	Handout outline to students
We talked about the following subjects the past 1½ hours.	
* Forces of Gravity and Buoyancy	413-2.26
* Aerodynamic Drag force on a particle in motion	
* Drag Coefficient	
* The three Regimes a particle flows in	413-2.27
• Laminar - Stokes Law Regime	
• Transition Regime	
• Turbulent - Newton's Regime	
* Cunningham correction factor for drag coefficient in the Laminar regime.	413-2-28
* The terminal settling velocity	
* The parameter K - to determine the proper regime	

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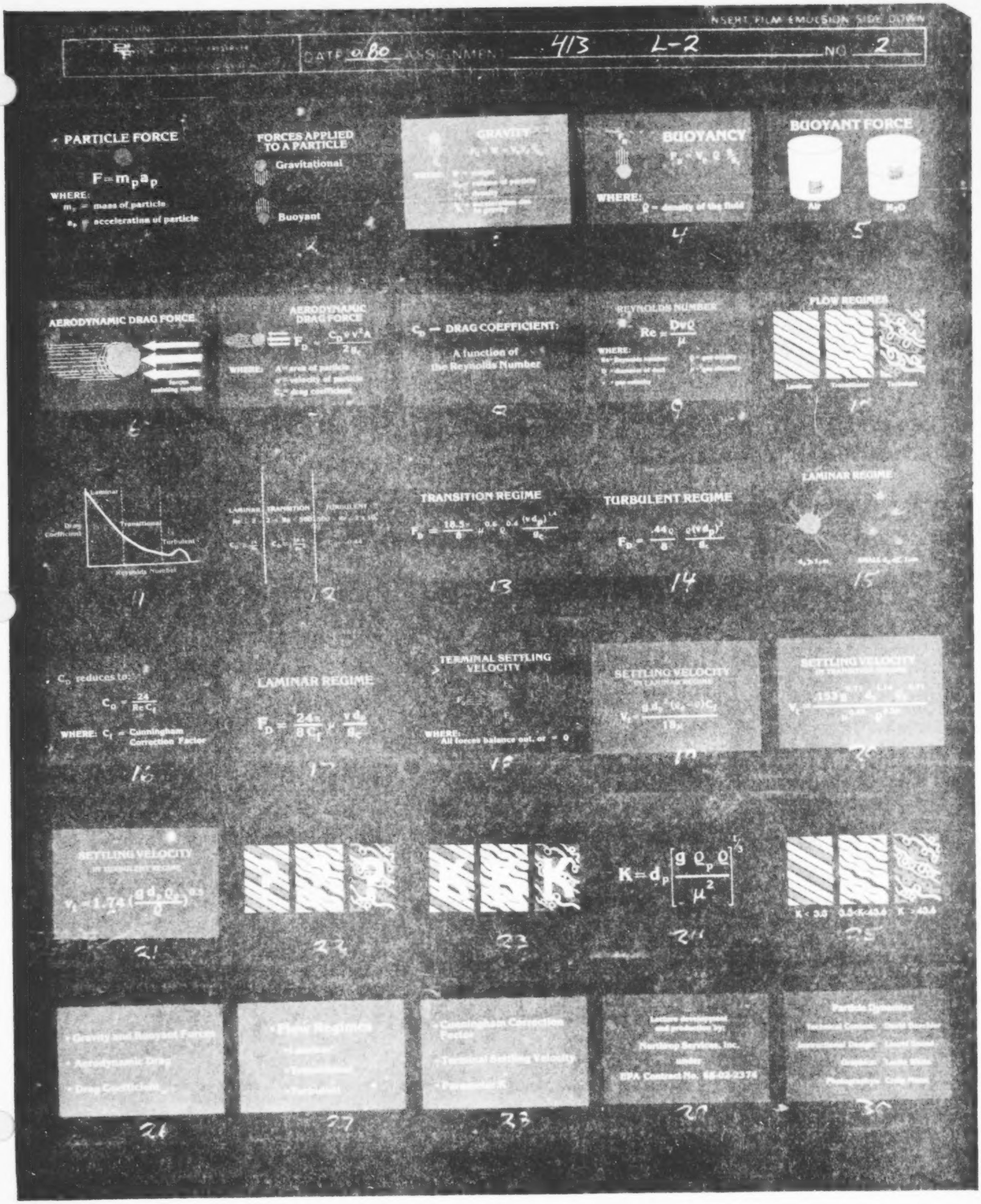

PARTICLE FORCE

$F = m_p a_p$

WHERE:
m_p = mass of particle
a_p = acceleration of particle

FORCES APPLIED TO A PARTICLE
Gravitational
Buoyant

2

GRAVITY

BUOYANCY
WHERE:
ρ = density of the fluid

4

BUOYANT FORCE
Air
H_2O

5

AERODYNAMIC DRAG FORCE
forces resisting motion

6

AERODYNAMIC DRAG FORCE

$F_D = \frac{C_D \rho v^2 A}{2 g_c}$

WHERE: A = area of particle
v = velocity of particle
C_D = drag coefficient

C_D — DRAG COEFFICIENT:
A function of the Reynolds Number

8

REYNOLDS NUMBER

$Re = \frac{D v \rho}{\mu}$

WHERE:

9

FLOW REGIMES

10

Laminar
Drag Coefficient
Transitional
Turbulent
Reynolds Number

11

LAMINAR | TRANSITION | TURBULENT

12

TRANSITION REGIME

$F_D = \frac{18.5\pi}{8} \mu^{0.6} \rho^{0.4} \frac{(v d_p)^{1.4}}{g_c}$

13

TURBULENT REGIME

$F_D = \frac{.44\pi}{8} \frac{\rho (v d_p)^2}{g_c}$

14

LAMINAR REGIME

15

C_D reduces to:

$C_D = \frac{24}{Re\, C_f}$

WHERE: C_f = Cunningham Correction Factor

16

LAMINAR REGIME

$F_D = \frac{24\pi}{8 C_f} \mu \frac{v d_p}{g_c}$

17

TERMINAL SETTLING VELOCITY

WHERE:
All forces balance out, or = 0

18

SETTLING VELOCITY
IN LAMINAR REGIME

19

SETTLING VELOCITY
IN TRANSITION REGIME

20

SETTLING VELOCITY
IN TURBULENT REGIME

$v_t = 1.74 \left(\frac{g d_p \rho_p}{\rho} \right)^{0.5}$

21

22

K

23

$K = d_p \left[\frac{g \rho_p \rho}{\mu^2} \right]^{1/3}$

24

K < 3.0 3.5<K<43.6 K > 43.6

25

- Gravity and Buoyant Forces
- Aerodynamic Drag
- Drag Coefficient

26

- Flow Regimes

27

- Cunningham Correction Factor
- Terminal Settling Velocity
- Parameter K

28

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Particle Dynamics

30

LESSON PLAN

AIR POLLUTION TRAINING INSTITUTE

TOPIC: PROBLEM SESSION I
PARTICLE DYNAMICS

COURSE: 413 - Lesson 2a
LESSON TIME: 30 minutes
PREPARED BY: David Beachler
DATE: 7/79

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

LESSON GOAL:	Briefly describe the use of the settling velocity, drag coefficient and drag force formulas by solving two problems.
SUPPORT MATERIAL AND EQUIPMENT	1. Chalkboard 2. 413 Student Workbook. pp 1-2

CONTENT OUTLINE

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

Course: 413 - Lesson 2a
Lecture Title: PARTICLE DYNAMICS-PROBLEM SESSION I

Page 1 of 2

NOTES

I. PROBLEM 1-1

A. Work out problem 1-1 for the students. The solution for 1-1 is:

NOTE: See problem 1-1 on page 1 of the 413 Student Workbook

1.1 Drag Coefficient and Settling Velocity

A spherical limestone particle is 400 μm in diameter, specific gravity = 2.67. Calculate the drag coefficient C_D and the settling velocity v_t in 70° F air.

SOLUTION:

1. Convert dp to feet

$$400\ \mu m \times \frac{1\ ft}{3.05 \times 10^5 \mu m} = 0.00131\ ft$$

2. Calculate K to determine regime

$$K = d_p \left[g\ \rho_p\ \rho / \mu^2 \right]^{1/2}$$

$$= \underset{ft}{0.00131} \left[\underset{ft/sec^2}{32.1} \times \underset{lb\ m/ft^3}{2.67 \times 62.4} \times \underset{lbm/ft^3}{0.075} \Big/ \underset{lbm/ft\ sec}{(1.23 \times 10^{-5})^2} \right]^{\frac{1}{2}}$$

$= 18.2 \rightarrow$ transition
$3.3 < K < 43.6$

Can we calculate C_D?

For transition regime, $C_D = 18.5 / Re^{0.6}$

But we don't know Re until we know v. So we have to determine settling velocity first.

3. Calculate settling velocity

$$v = 0.153\ (g\ \rho_p)^{0.71}\ d_p^{1.14} \Big/ \rho^{0.29}\ \mu^{0.43}$$

$$= 0.153\ (32.1 \times 2.67 \times 62.4)^{0.71}\ (0.00131)^{1.14} \Big/ (0.075)^{0.29}\ (1.23 \times 10^{-5})^{0.43}$$

$= 9.62$ ft/sec

4. Calculate Re and C_D

$$Re = \frac{v\ d_p\ \rho}{\mu} = \frac{(9.62)\ (0.00131)\ (0.075)}{1.23 \times 10^{-5}} = 76.8$$

at expected, $2 < Re < 76.8$ for transition regime

$$C_D = \frac{18.5}{Re^{0.6}} = 1.37$$

Check with C_D versus Re curve in the 413 Manual; at Re = 76.8, $C_D \sim 1.3$ so it agrees with our calculation.

II. Problem 1-2

A. Allow students 15 minutes to work on problem 1-2.

B. Go over the solution of problem 1-2. The solution is:

NOTE: See problem 1-2 on page 2 of the 413 Student Workbook

1-2. Settling Velocity and Drag Force

Particles 20 microns in diameter at 70°F with a specific gravity of 1.8 flow in a duct. The density of H_2O is 62.4, the density of air is 0.075 $\frac{lb}{ft^3}$ and the viscosity of air is $1.23 \times 10^{-5} \frac{lb}{ft\text{-}sec}$.

(a) Calculate the settling velocity

1. Convert to feet

$$20\ \mu m \times \frac{1\ ft}{3.05 \times 10^5\ \mu m} = .000065\ ft.$$

2. Calculate K to determine the regime

$$K = d_p \left[g\rho_p\rho/\mu^2 \right]^{1/3}$$

$$K = .000065 \left[\frac{32.1 \times 1.8 \times 62.4 \times .075}{(1.23 \times 10^{-5})^2} \right]^{0.5}$$

$$K = 87.6$$

3. Use $v_t = 1.74\ (g\ d_p\ \rho_{p/\rho})^{0.5}$

$$v_t = 1.74 \times \left[\frac{32.1 \times .000065 \times 62.4 \times 1.8}{.075} \right]^{0.5}$$

$$v_t = 3.089\ ft/sec$$

(b) Calculate the Drag Force

$$F_D = 0.055\ \pi\ (d_p\ v)^2\ \rho/g_c$$

$$= \frac{0.055\ \pi \times (0.000065 \times 3.089)^2 \times 0.075}{32.1}$$

$$= 1.63 \times 10^{-11}\ lb_f$$

LESSON PLAN

AIR POLLUTION TRAINING INSTITUTE

TOPIC: PARTICLE SIZING - MEASUREMENT AND MATHEMATICAL METHODS

COURSE: 413 - Lesson 3
LESSON TIME: 1 hour
PREPARED BY: David Beachler
DATE: 4/18/79

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

LESSON GOAL: Describe the common particle measuring methods and describe the mathematical methods for determining particle size focusing on the log-normal distribution.

LESSON OBJECTIVES: At the end of the lesson the student should be able to:

- Recognize five methods of measuring the size of a particle and briefly describe their operation.
- List the three most important parameters used to rate a particle sizing device.
- Describe the major advantages and disadvantages of each of the five particle measuring devices.
- Discuss how one can obtain the actual sample from a source and the subsequent analysis for particle size distributions for each of the measuring devices
- Describe the aerodynamic diameter of a particle.
- Discuss how one can estimate a typical particle size distribution from a proposed new source.
- Recognize three typical mathematical methods dealing with particle size distribution.
- Describe the log-normal distribution and the shape of the curves when plotted on various scales.
- Describe the geometric mean and standard deviation and how they can be calculated for a log-normal distribution.

STUDENT PREREQUISITE SKILLS

Ability to understand basic principles of physical science.

LEVEL OF INSTRUCTION

Advanced

INTENDED STUDENT PROFESSIONAL BACKGROUND

Engineering or physical science

SUPPORT MATERIALS AND EQUIPMENT

1. Slide projector
2. Overhead projector
3. Chalkboard
4. 413 Student Manual

REFERENCES:

1. 413 Student Manual
2. 413 Student Workbook pp. 3-5
3. Lecture notes prepared by Cliff I. Davidson, Carnegie Mellon University, March 1979.
4. "Particle Size Analysis", John D. Stockham and Edward G. Fochtman, Ann Arbor Science, 1977, pp. 1-127.
5. "Proceedings: Advances in Particle Sampling and Measurement", EPA-600-7-79-065, February 1979, IERL, RTP, NC 27711.

AUDIO-VISUAL MATERIALS FOR LESSON 3

Lesson 3 Particle Sizing

413-3-1	Manual measurement methods
413-3-2	Mathematical treatment of data
413-3-3	Aerodynamic diameter
413-3-4	Ideal measuring device
413-3-5	Ideal measuring device
413-3-6	Ideal measuring device
413-3-7	Rating measuring devices--key
413-3-8	Rating measuring devices--key
413-3-9	Rating measuring devices--key
413-3-10	Ideal measuring device
413-3-11	Microscopy
413-3-12	Microscopy rating
413-3-13	Microscope measuring size range
413-3-14	Optical particle counter
413-3-15	Optical particle counter rating
413-3-16	Optical particle counter measuring size range
413-3-17	Electrical aerosol analyzer
413-3-18	Electrical aerosol analyzer rating
413-3-19	Electrical aerosol analyzer measuring size range
413-3-20	Bahco sampler
413-3-21	Bahco sampler rating
413-3-22	Bahco sampler measuring size range
413-3-23	Cascade impactor
413-3-24	Cascade impactor rating
413-3-25	Cascade impactor measuring size range
413-3-26	Normal distribution
413-3-27	Log-normal distribution--linear d_p plot
413-3-28	Log normal distribution--log scale d_p plot
413-3-29	Cumulative log-normal distribution
413-3-30	Expansion of scale
413-3-31	Log-normal distribution--plot on log probability paper
413-3-32	Log-normal distribution--geometric mean on plot
413-3-33	Geometric standard deviation
413-3-34	Geometric standard deviation

CONTENT OUTLINE

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

Course: 413 Lesson 3
Lecture Title: PARTICLE SIZING

NOTES

I. Introduction

- A. When trying to design air pollution control equipment to control particulate emissions from an industrial source, it is necessary to determine the size distribution of the particles being collected in order to accurately calculate the efficiency of the control device.

- B. Basically there are two ways to determine particle size distribution that we will talk about: — 413-3.1, 413-3.2
    1. Measurement methods
    2. Mathematical treatment of data

II. Size - In discussing particle size we want to first take a look at what "size" or what "diameters" one can consider.

- A. An average diameter is the diameter of a hypothetical particle which in some way represents the total number of particles in the sample.

- B. Diameters representing length, surface area, volume, specific surface, weight, and falling speed can be determined.

- C. The average diameter that best characterizes the process variable under study should be chosen. i.e., projected area is important to pigments, while total surface is important for chemical reactants.

- D. With many aerosols, interest is centered on the aerodynamic behavior of the particle, this is also called the Stokes diameter and is a function of geometric diameter, shape, and density of the particle. This tells us how a particle behaves on an air stream. Aerodynamic diameter is more useful than the geometric diameter and is usually measured by an impactor which will be discussed later in the lecture. — 413-3.3

III. Measurement Methods

- A. The ideal particle measuring device would: — 413-3.4
    1. Measure exact size of each individual particle
    2. Yield instantaneous response - NO LAG TIME or averaging time — 413-3.5
    3. Determine complete composition of each particle (i.e., shape, density, etc.) — 413-3.6

B. Examine five measurement devices and compare the advantages and disadvantages of each, by rating each for size, time, composition.

   1. Rating scale denoting resolution at single particle level (is represented by Slide) i.e., size of each particle

      413-3.7

   2. Discrete ranges -- (denoted by slide) i.e., size ranges of particles

      413-3.8

   3. Integrated average (denoted by Slide) i.e., total mass of particles of all sizes

      413-3.9

   4. The ideal device would be

      413-3.10

C. We will also consider the various measurement devices as to their effectiveness for different size diameters. i.e., some devices are quite useful for submicron particles, others are not.

IV. Individual Particle Measuring Devices

A. There are many ways (devices) one can use to measure the size of a particle but we will only consider five different kinds and try to compare these devices. (The 413 Manual discusses some additional devices).

B. Types of Devices

   413-3.11

   1. Microscope - optical or electron microscope

      a. Individual particle sizing, but very long and tedious process. Not very useful for routine measurements.

      b. The particles can be collected on a filter by using an EPA Method 5 sampling train. The filter is then taken to the lab to be analyzed under the microscope.

         413-3.12

      c. The size is measured at the individual level.

      d. Time - that measuring occurs is averaged.

      e. Little information on the composition of the particle. Generally speaking one is not able to obtain the chemical composition of the particle when using an optical microscope.

      f. When using an electron microscope one can get a detailed chemical analysis of the individual particle.

      g. The microscope measures the geometric diameter of the particle - measured distance across the particle.

      h. The optical microscope can measure particles from about .5 microns to about 100 microns. The electronic microscope can measure particles as small as .001 microns.

         413-3.13

2. Optical Particle Counter - Light scattering 413-3.14

   a. The optical counter can be used for taking a sample from a source stack by inserting a probe into the stack.

   b. The flow stream into the measuring device must be diluted with air -- so that one can insure that one particle passes through the sensing volume (chamber) at a time.

   c. Particles pass individually through a light beam; split second measurement; scattering of light is related to particle size.

   d. Instrument categorizes particles into size ranges, discrete size ranges 413-3.15

   e. Perfect time resolution - if there is an instantaneous burst of particle emissions from a source, it can be detected.

   f. No particle composition information since the particles pass through the sensing volume and are not collected.

   g. The optical counter is difficult to use for source sampling (requires dilution) and interferences due to variations in particle shape, index of refraction and optical adsorptivity can affect readings.

   h. The optical counter measures particles from about .01 microns to 10 microns in diameter. 413-3.16

3. Electrical Aerosol Analyzer

   a. Measuring mobilities of charged aerosols. Aerosols pass through an electric field and the charged particles migrate over to a collecting surface. 413-3.17

   b. Mobility depends on particle size -- therefore divided into size ranges 413-3.18

   c. You have to wait for enough particles to pass through the instrument to get a detectable charge -- therefore time increments while charge builds up.

   d. This type of analyzer has been used in a stack by pulling the particles from the stack into a chamber and introducing this gas stream into the analyzer. However usefulness of the data obtained from this type of analyzer is very skeptical due to the complexity of measuring the charge of an individual particle.

   e. This analyzer is used mostly for controlled lab experiments where aerosols are generated and introduced into the analyzer.

f. No information on composition since the particles are not collected. — 413-3.19

g. A major advantage is that size information can be obtained for very small particles down to .005 μm in diameter.

4. Bahco - microparticle classifier — 413-3.20

   a. The particles can be collected (grab sample) by using a Method 5 type sampling train onto a filter and then taken back to the lab for analysis

   b. The Bahco uses a combination of elutriation and centrifugation to separate particles in an air stream.

      (1) The weighed sample is introduced into a spiral-shaped air current flowing towards the center.

      (2) The spiral current of air has suitable values of tangential and radial velocities so that a certain part of the sample is accelerated by the centrifugal force toward the pheriphery of the whirl, the other part of the sample being carried by the air current toward the center of the whirl by means of friction between the air and the dust particle.

      (3) The size, shape and density of the particle determine which direction it will take. By varying the flow, the material can be divided into a number of fractions.

   c. Size - measured in size ranges -- therefore discrete ranges. — 413-3.21

   d. Time - it takes several hours to complete the fraction analysis--therefore average time values

   e. Can do a chemical analysis on each size range of collected particles.

   f. Bahco provides information on the aerodynamic size of particles, which can be translated into settling velocity information useful for designing emission control devices. — 413-3.22

   g. The major drawbacks are:

      (1) The working range is from 1 to 60 microns in diameter

      (2) Care must be exercised when measuring certain type particles especially those which are friable and hygroscopic.

5. Impactor - inertial impactor

Collects and separates particles into size ranges

This device actually collects particles, so we can do chemical analysis to determine composition for different size ranges.

a. The inertial impactor can be attached to a standard sampling train (Method 5) and inserted into the stack.

b. The particles are collected on individual stages (usually with filters made of paper or aluminum foil -- preweighed) and once the sample is complete, the collection filters are weighed giving particle size distribution data for the various collection stages.

c. Description -- Device operates on the principle of inertial impaction -- large particles cannot follow air streamlines around an obstacle: 413-3.23

d. Size - measured in size ranges -- discrete ranges 413-3.24

e. Time - averaged values

f. Can do chemical analysis on collected particles in each size range

g. Impactor measures the aerodynamic diameter. This is a function of geometric diameter, shape and density of the particle. This tells us how a particle behaves in an airstream. Aerodynamic diameter is a more useful value than the geometric diameter.

h. The effective cut off range is around .02 to 20 microns in diameter. 413-3.25

i. This is probably most useful device for the control agency or source operator to use to determine the particle size distribution from a particular source. This is due to the fact that these instruments have been used for some time, the ability to draw a sample directly from a stack and the relative inexpensiveness of the equipment.

V. Obtaining Size Distribution Data from a New Source

A. Sometimes the source operator or control agency officer is in the perplexing position of trying to obtain particle size data from a process that has not yet been built.

B. Under these circumstances they are left with no option but to obtain the data from published size distribution data of similar installations already in operation.

C. Some useful sources of information include:

1. Many EPA publications on particle size.

2. "Particulates and Fine Dust Removal", Marshall Sittig, Pollution Control Review No. 34, published by Noyes Data Corporation, Park Ridge, New Jersey, 1977.

VI. Mathematical Treatment of Data

In dealing with particle size distributions, the 413 Manual discusses several typical size distributions. Some include:

A. Normal Distribution; bell-shaped on a linear d_p scale versus percent of total particle mass. 413-3.26

B. Bi-model Distribution --with two bell shaped peaks

C. Log-normal Distribution--we will focus on this one more.

1. Log-normal distribution plotted on a liner d_p scale is skewed — 413-3.27

2. Log-normal distribution plotted on a logarithmic d_p scale is a symmetrical bell shaped curve — 413-3.28

3. The log-normal distribution is often plotted as a cumulative distribution. Cumulative log-normal plotted on linear percentage scale approaches 0% and 100% values asymptotically when d_p is on a logarithmic scale. (The ends of the curve 0% has $d_p > \infty$, 100% has $d_p > 0$) — 413-3.29

4. Using a special type of graph paper called: — 413-3.30

   a. log probability paper, one can expand the cumulative distribution axis near 0% and near 100%. By expanding the axis, we can force the bell-shaped curve to be a straight line.

   b. The plot is identical to the previous plot, except that the percentage scale is expanded near 0% and 100%. — 413-3.31

      (Note the straight line does not have to cross the graph at the 50% point)

5. Geometric mean and standard deviation of a log-normal distribution.

   (a) On a plot of particle diameter d_p (log scale) versus cumulative percent larger than the maximum diameter d_p max;

      (1) the geometric mean is midway between the 84.13% size and the 15.8% size -- or at the 50% size — 413-3.32

(2) The standard deviation is the root-mean-square deviation about the mean value. It's derivation and application in significant testing and setting of confidence levels can be found in most textbooks on statistics. 413-3.33

(3) geometric standard deviation is the: 413-3.34

$$\sigma_{gm} = \frac{50\%\ \text{size}}{84.13\%\ \text{size}} = \frac{15.87\%\ \text{size}}{50\%\ \text{size}}$$

b. The utility and importance of the log-normal distribution of particle sizes is summarized:

(1) The distribuiton is completely specified by the two parameters, the geometric median particle size, d_g, and the geometric standard deviation, σ_{gm}.

(2) The geometric standard deviation is identical for all methods for specifying the particle size distribution, whether by particle number, surface, mass or any other quantity of the form kd^n, where d is the diameter and k is a parameter common to all particles. Plots of the cumulative distribution on log-probability paper are then parallel straight lines for number, mass or surface which leads to a great simplification and simple graphical technique.

(3) Transformations among the various particle size paramters and statistical diameters are greatly facilitated both analytically and graphically.

(4) The geometric mean diameter, d_g, and the geometric standard deviation, σ_{gm}, may be found by a simple graphical procedure as illustrated in Figure 2.

(5) The geometric mean diameter, d_g, is equal to the median or central value of the distribution.

Figure #1

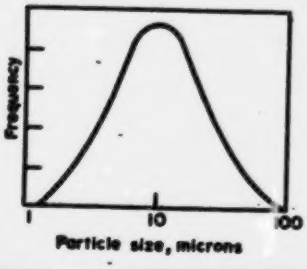
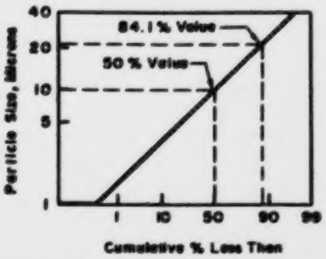


Figure 1. Particle size distribution of Figure 2 plotted with logarithm of particle size.

Figure #2



VI. Review

We have talked for the past 1 hour about the following subjects:

- Five methods of measuring particles
- Three parameters to rate a particle sizing device.
- Aerodynamic diameter of a particle
- Sampling methods for taking the particles from a source and measuring their size.
- Methods of estimating particle size data from new sources.
- Mathematical methods dealing with particle size distribution
- Lognormal distribution
- Geometric mean and standard deviation of a lognormal distribution

AERODYNAMIC DIAMETER:
IDEAL MEASURING DEVICE
KEY
KEY
KEY
MICROSCOPY
1
2
3

DATE 6/80 ASSIGNMENT 413 L-3 NO.

3-1

3-2

GEOMETRIC STANDARD DEVIATION

3-3

GEOMETRIC STANDARD DEVIATION

3-4

3-5

LESSON PLAN

AIR POLLUTION
TRAINING INSTITUTE

TOPIC: PROBLEM SESSION II
PARTICLE SIZING

COURSE: 413 - Lesson 3a
LESSON TIME: 1/2 hour
PREPARED BY: D. Beachler **DATE:** 7/79

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

LESSON GOAL: Briefly describe the use of log-normal distribution data and calculate the geometric mean and standard deviation by solving two problems.

SUPPORT MATERIALS
AND EQUIPMENT:

1. Chalkboard
2. 413 Student Workbook pp. 3-5.

I. Problem 2-1.

A. Work out problem 2-1 for the students.

The solution for 2-1 is:

(See Next Page)

Note: See problem 2-1 on page 3 of the 413 Student Workbook.

2.1 Log-normal distribution

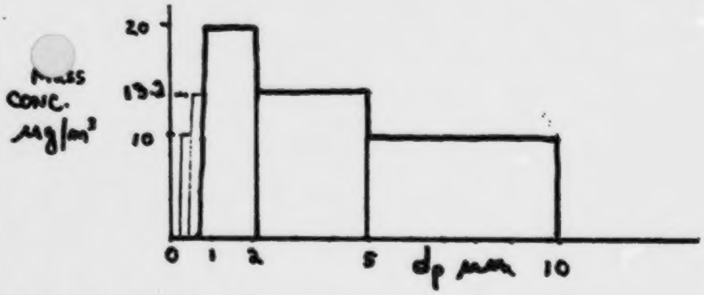
Let's say you have collected some data on particle mass concentration with an optical particle counter or an Anderson Impactor. The following data was collected.

d_p range μm	concentration μg/m^3
0.1 - 0.2	10
0.2 - 0.5	13.2
0.5 - 2	20
2 - 5	13.2
5 - 10	10

How can you tell if these data represent a log normal distribution or some other distribution?

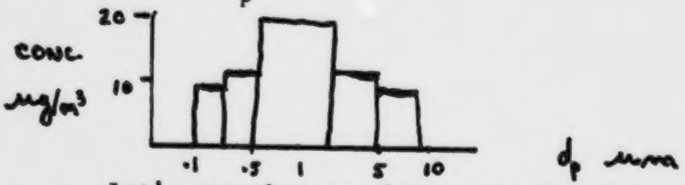
SOLUTION:

1. Plot mass concentration on a linear d_p scale.



skewed shape
which 413 Manual says is characteristic of a lognormal curve.

2. Log d_p scale



We do get an appropriate bell-shaped curve. But is the distribution lognormal?

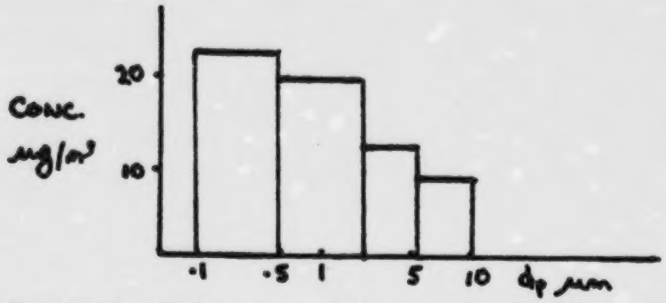
(throwing a curve on this one)

Let's say that our instrument just measures 4 size ranges, lowest range is 0.1 - 0.5 μm

New device same

d_p range	concentration
0.1 - 0.5 μm	23.2 μg/m^3
0.5 - 2.0	20.0
2.0 - 5.0	13.2
5 - 10	10

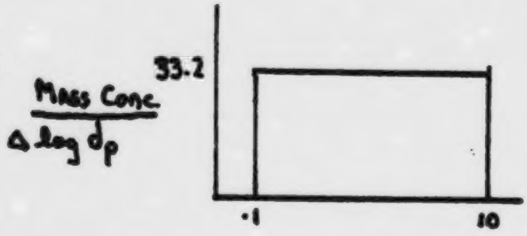
Actual size distribution is the same, but we just have a different measurement device



Problem: each size range covers a different interval.
So we can make any shape distribution we want just by using instruments with certain size range intervals!

Obviously, there is a "true" distribution. Add new column in table:

d_p range	Conc	Conc ÷ Δ log d_p
0.1 - 0.2	10	10 ÷ (log 0.2 - log 0.1) = 33.2
0.2 - 0.5	13	33.2
0.5 - 2	20	33.2
2 - 5	13.2	33.2
5 - 10	10	33.2



True distribution = uniform in log d_p

We can easily recover the mass concentration by integrating:

Mass conc. between 0.1 µm and 0.2 µm

$$= \int_{\log 0.1}^{\log 0.2} \frac{\text{Mass conc}}{\Delta \log d_p} \; d \log d_p$$

So area under this curve is equal to mass in any size interval.

CONTENT OUTLINE

Course: 413 - Lesson 3a
Lecture Title: PARTICLE SIZING - PROBLEM SESSION II

II. Problem 2-2.

A. Allow students 10 minutes to work on problem 2-2.

B. Go over the solution for 2-2.

The solution for 2-2 is:

(See Next Page)

NOTES

Note: See problem 2-2 on page 4 of the 413 Student Workbook.

2.2 Log-normal distribution, geometric mean and standard deviation

Given the following particle size data:

Size Range d_p in μm	Mass Concentration μg/m^3
< 0.1	0.04
0.1 - 0.2	0.76
0.2 - 0.5	15.07
0.5 - 2.0	68.26
2.0 - 5.0	15.07
5.0 -10.0	0.76
< 10.0	0.04

Verify that this distribution is approximately log-normal, and find the geometric mean and the geometric standard deviation.

Hint: determine the percentage mass larger than d_p max in each size range. You don't need log probability paper to do this problem.

SOLUTION:

Verify bell-shaped curve		Mass Conc ÷ Δ log d_p
<0.1	0.04	----
0.1 - 0.2	0.76	0.76 ÷ 0.301 = 2.52
0.2 - 0.5	15.07	37.9
0.5 - 2	68.26	113.4
2 - 5	15.07	37.9
5 -10	0.76	2.52
>10	0.04	----

(bell-shaped with a peak between 0.5 and 2 μm)

Better to use log probability paper and see if you get a straight line.

To find geom. mean and standard deviation, list % mass larger than d_p max.

	mass conc. Δlog d_p	% Mass > d_p max
0.04	-----	99.96%
0.76	2.52	99.2
15.07	37.9	84.13
68.26	113.4	15.87
15.07	37.9	0.8
0.76	2.52	0.04
0.04	-----	0
Total 100.00 μg/m^3		

Geom. mean = size midway between 15.87% size and 84.13% size on a log scale

Geometric mean = midway between 0.5 and 2 = 1 μm

Geometric standard deviation

$$= \sigma_{gm} = \frac{50\%\ \text{size}}{84.13\%\ \text{size}} = \frac{1\ \mu m}{0.5\ \mu m} = 2$$

III. Problem 2-3

A. Have students do problem 2-3 for homework.

B. Go over the solution for 2-3. The solution is:

(See Next Page)

NOTES

Note: See problem 2-3 on page 5 in the 413 Student Workbook.

2.3 Given the following distributions obtained from size differentiating equipment:

Particle Size d_ρ (microns)	Distribution A $\mu g/m^3$	Distribution B $\mu g/m^3$
<0.62	25.5	8.5
0.62 - 1.0	33.15	11.05
1.0 - 1.2	17.85	7.65
1.2 - 3.0	102.0	40.8
3.0 - 8.0	63.75	15.3
8.0 -10.0	5.1	1.692
< 10.0	7.65	0.008

(a) Is either distribution A or distribution B log-normal?

(b) If so, what is the geometric mean and standard deviation.

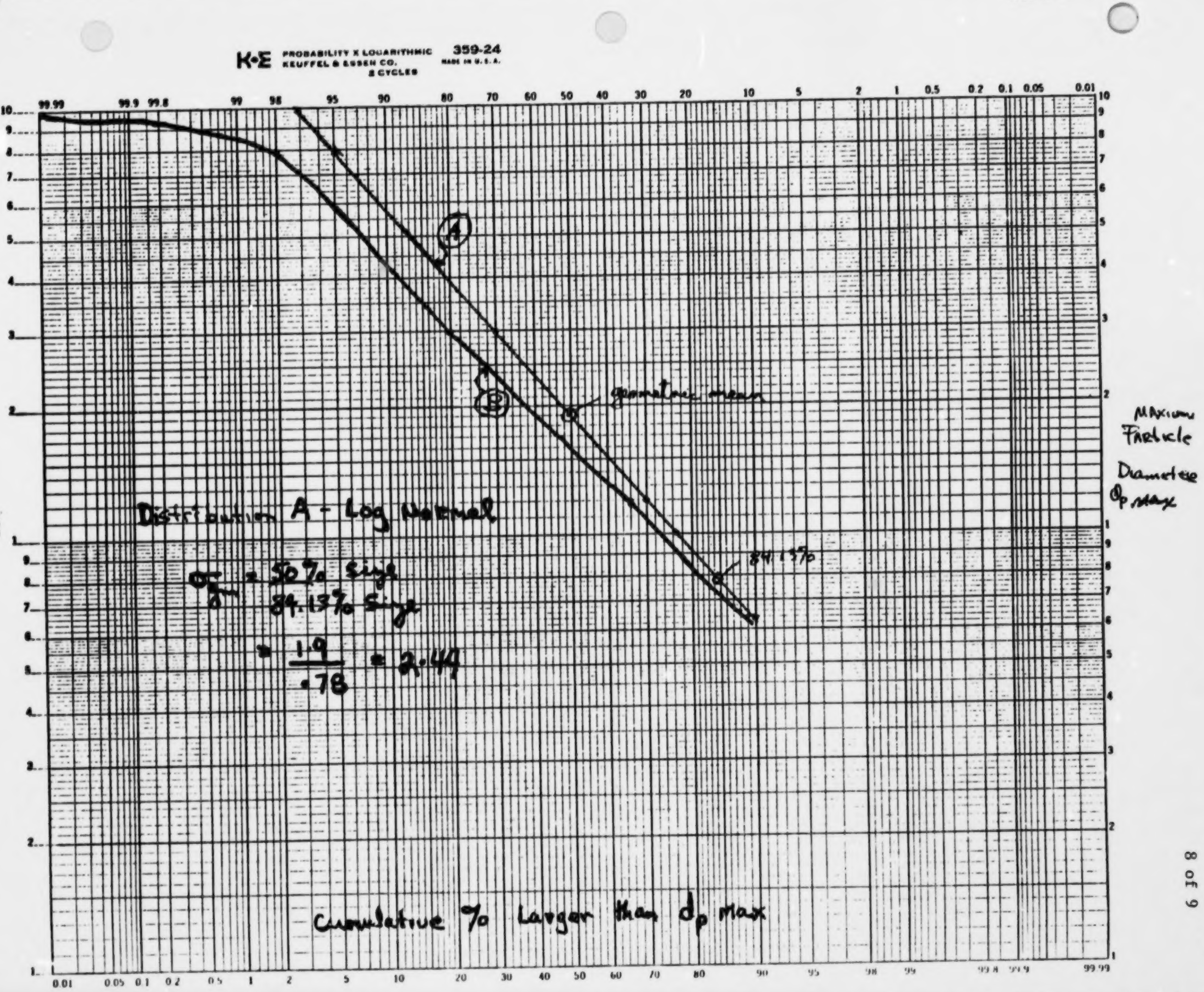
(Use the sheet of log probability paper provided on page 6 of 413 Workbook if necessary.)

SOLUTION:

Make a cumulative distribution plot on log-probability paper.

		Distribution A % of total = 255 $\frac{\mu g}{m^3}$	cum % larger than d_p mas
< 0.62	$\frac{25.5}{255}$ =	10%	90
0.62 - 1.0		13	77
1.0 - 1.2		7	70
1.2 - 3.0		40	30
3.0 - 8.0		25	5
8.0 -10.0		2	3
>10		3	0

		Distribution B % of total = 85%	Cum %
< 0.62	$\frac{8.5}{85}$ =	10%	90
0.62 - 1.0		13	77
1.0 - 1.2		9	68
1.2 - 3.0		48	20
3.0 - 8.0		18	2
8.0 - 10.0		2	0.01
>>10		0.01	0



Distribution A - Log Normal

$$\sigma_g = \frac{50\% \text{ Size}}{84.13\% \text{ Size}} = \frac{1.9}{.78} = 2.44$$

2.3 SOLUTIONS (cont'd)

1. Plot cumulative % larger than d_p max versus d_p max on log probability paper.

2. If the plot yields a straight line the distribution is log normal. Distribution A is log normal, distribution is not.

3. Geometric mean (for distribution A)

$$\sigma_{gm} = \frac{50\%\ \text{size}}{84.13\%\ \text{size}}$$

$$\sigma_{gm} = \frac{1.9\ \mu m}{0.78\ \mu m} = 2.44$$

LESSON PLAN

AIR POLLUTION TRAINING INSTITUTE

TOPIC: METHODS FOR REDUCING PARTICULATE EMISSIONS

COURSE: 413 Lesson 4
LESSON TIME: 1/2 hour
PREPARED BY: D. Beachler **DATE:** 4/79

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

LESSON GOAL:	Introduce the main methods for collection of particulate emissions; emission reduction methods without the use of emission control equipment.

LESSON OBJECTIVES: At the end of the lesson the student should be able to:

- * List four major ways to eliminate or reduce emissions from an air pollution stationary source.
- * List three modifications in the operation of a source to reduce the emissions without the use of air pollution control equipment.
- * Name the five basic types of emission control equipment used for control of particulate emissions.
- * List the forces used in the removal of particles from exhaust gas streams.
- * Recall the formula to calculate the efficiency of an air pollution control device by weight.

STUDENT PREREQUISITE SKILLS:	Ability to understand basic principles of physical science.
LEVEL OF INSTRUCTION:	Intermediate
INTENDED STUDENT PROFESSIONAL BACKGROUND:	Engineering or Physical Science

SUPPORT MATERIALS AND EQUIPMENT:

1. slide projector
2. overhead projector
3. chalkboard
4. 413 Student Manual

REFERENCES:

1. 413 Student Manual
2. "Air Pollution Control Technology, an Engineering Analysis Point of View," by Robert M. Bethea, Van Nostrand Reinhold Company, New York, 1978. pp. 61-105.

AUDIO-VISUAL MATERIALS FOR LESSON 4

Lesson 4 Methods for Reducing Particulate Emissions

413-4-1	Reducing emissions
413-4-2	Dry collectors
413-4-3	Wet collectors
413-4-4	Forces used in collection equipment
413-4-5	Gravitation
413-4-6	Centrifugal force
413-4-7	Impaction
413-4-8	Direct interception
413-4-9	Diffusion
413-4-10	Electrostatic attraction
413-4-11	Evaluating a control device
413-4-12	Efficiency of a control device

CONTENT OUTLINE

Course: 413 Lesson 4
Lecture Title: METHODS OF PARTICLE COLLECTION

Page 1 of 4

NOTES

I. Control Methodology

The technology of source control consists of all of the sciences and techniques that can be brought to bear on the problem of controlling air pollution. To eliminate or reduce emissions from a polluting operation or to reduce their impact, there are four major courses of action.

Slide: 413 - 4-1

- Substitute a different process, fuel, material, or device
- Regulate the location of the operation
- Modify the operation
- Apply air pollution control devices

A. Substitute a different process, fuel, material or device:

1. The emissions from an operation or activity can be removed by eliminating the operation. Examples:
   - (a) open burning - use of sanitary landfill
   - (b) single chamber incinerators -- the use of multiple chamber incinerators
   - (c) hand fired coal burning boilers -- automatic coal stokers or use of natural gas or oil.
   - (d) bee hive coke ovens -- use of by-product coke batteries.

B. Regulate the location of operation

1. Applying zoning ordinance to locate or distribute sources of air pollution.
2. Imposing area limits on emissions rates that have been derived from air quality standards.

Both approaches 1. and 2. may be implemented by regulatory standards, land use planning and zoning controls, and by special handling i.e. land use permit cases.

3. New source construction permit programs which prohibit emissions which cause NAAQS or PSD increments to be exceeded.
4. Special handling option, i.e. can locate the air pollution source downwind of the urban area of the town -- create uninhabited areas around the source.

C. Modification of Operation

1. Control methods (without control devices)
2. Process change
    - (a) control of fugitive dust
        - (1) watering of roads
        - (2) paving roads with asphalt
        - (3) covering open bodied trucks that haul -- coal in or fly ash out
        - (4) storage piles of materials -- control sprays, cover, etc.
        - (5) enclosing of operation, i.e. sandblasting from outside -- to enclose area and use hoods, fans, and ducting
3. Good operating practices -- maintenance
    - (a) odors from food processing plants can be eliminated by good housekeeping
    - (b) operating the equipment at the designed rate -- i.e. a rotary sand and stone drier for asphalt plants when operated above design rate tends to increase the dust emissions greater than the increase in gas flow
    - (c) reclaiming scrap steel -- strip the cars of upholstery, plastic, rubber before melting -- smoke from oily scrap can be avoided
4. Use of tall stacks
    - (a) use the appropriate stack height to eliminate downwash and eddies from stack.
5. Change in fuel source
    - (a) use of oil or natural gas instead of coal -- for smaller sources
    - (b) use of low sulfur fuels
    - (c) pre-cleaning -- or washing of coals

6. Use CO from cat cracker for boiler fuel and eliminate CO emissions
7. Use water instead of HC for carrier in paint operation.
8. Use atomizing burners instead of rotary cup burners in process boilers.
9. Plant shutdown -- as last resort

D. Apply Air Pollution Control Devices

This is what we will be dealing with most in this course -- the application of particulate air pollution control devices

1. We'll talk about the various types of control devices

   Slide: 413 - 4-2
   413 - 4-3

   (a) dry collectors
      - gravity settling chambers
      - inertial separators
      - cyclones
      - electrostatic precipitators
      - fabric filters

   (b) wet collectors, i.e.,
      - wet scrubbers
      - spray towers
      - venturi scrubbers
      - impingement plate scrubbers
      - dynamic centrifugal scrubbers

2. We'll take a look at how the particles are collected in each type of equipment and the forces used to remove particles from a gas stream for each control device such as:
   * gravitational
   * centrifugal
   * impaction
   * interception
   * diffusion
   * electrostatic

   Slides: 413 - 4-3
   413 - 4-5
   413 - 4-6
   413 - 4-7
   413 - 4-8
   413 - 4-9
   413 - 4-10

3. We'll look at each type of particulate control device and characterize the equipment by looking at:
    * particle size (specific efficiency)
    * mass rate efficiency
    * pressure drop
    * space required
    * initial cost
    * operating cost

Slide: 413 - 4-11

4. When calculating the collection efficiency (by weight) of a specific type of control equipment in general one would use the formula:

$$\text{Eff.} = \frac{\text{wt. in} - \text{wt. out}}{\text{wt. in}}$$

Slide: 413 - 4-12

II. Review

The important things we will be doing in looking at the various types of particulate control devices will be

1. Look at the device and describe its basic operation
2. Look at the basic parameters of design and how to utilize these parameters to calculate the efficiency of the unit.
3. Work problems specific to each type of particulate control device calculating:
    a. pressure drop
    b. efficiency
    c. sizing dimension
4. Take a look at where these units are used in industries and the restrictions of use of equipment.

6/80 413 L-4 NO 4

REDUCING EMISSIONS

- Substitute fuel, process material or device
- Regulate location of operation
- Modify the operation
- Apply control devices

DRY COLLECTORS

- Gravity Settling Chamber
- Inertial Separators
- Cyclones
- Electrostatic Precipitators
- Fabric Filters

WET COLLECTORS

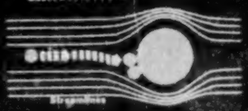
- Wet Scrubbers
- Spray Towers
- Venturi Scrubbers
- Impingement Plate Scrubbers
- Dynamic Centrifugal Scrubbers

FORCES USED IN COLLECTION EQUIPMENT

- Gravitational
- Centrifugal
- Impaction
- Interception
- Diffusion
- Electrostatic

4

GRAVITATION


Streamlines

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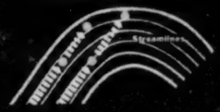
CENTRIFUGAL FORCE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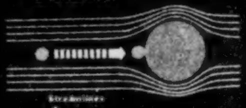
IMPACTION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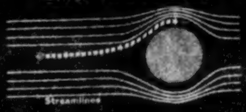
DIRECT INTERCEPTION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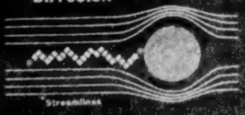
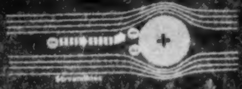
DIFFUSION


Streamlines

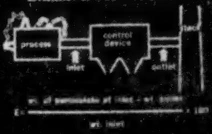
ELECTROSTATIC ATTRACTION


+
Streamlines

EVALUATING A CONTROL DEVICE

- Particle Size
- Efficiency
- Pressure Drop
- Space
- Initial Cost
- Operating Cost

EFFICIENCY OF A CONTROL DEVICE


process
control device
stack
inlet
outlet

$$E = \frac{\text{wt. of particulate at inlet} - \text{wt. outlet}}{\text{wt. inlet}} \times 100$$

Lecture development and production by:

Northrop Services, Inc.
under
EPA Contract No. 68-02-2374

Methods for Reducing Particulate Emissions

Technical Consult: [illegible]
Instructional Design: Karen Ludwig
Graphics: [illegible]
Photography: [illegible]

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LESSON PLAN

AIR POLLUTION TRAINING INSTITUTE

TOPIC: SETTLING CHAMBER - PRINCIPLES, OPERATION, AND APPLICATIONS

COURSE: 413 - Lesson 5
LESSON TIME: 1/2 hour
PREPARED BY: David S. Beachler
DATE: 4/79

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

LESSON GOAL: Briefly describe the theory behind the collection of particulates by settling chambers, their operation and calculations.

LESSON OBJECTIVES: At the end of the lesson the student should be able to:

- Describe the collection mechanisms which cause particles to be collected in a settling chamber
- List two types of settling chambers.
- Recognize Stokes Law for determining the settling velocity and calculate the settling velocity of a particle in a settling chamber.
- Recognize and use the equation for determining the minimum particle size collected in a settling chamber.
- Calculate the collection efficiency of a settling chamber.
- Describe the system design parameters used in designing settling chambers.

STUDENT PREREQUISITE SKILLS: Ability to understand basic principles of physical science

LEVEL OF INSTRUCTION: Intermediate

INTENDED STUDENT PROFESSIONAL BACKGROUND: Engineering or Physical Science

SUPPORT MATERIALS AND EQUIPMENT:

1. slide projector
2. overhead projector
3. chalkboard
4. 413 Student Manual

REFERENCES:

1. 413 Student Manual

2. "Air Pollution Control Technology, an Engineering Analysis Point of View", by Robert M. Bethea, Van Nostrand Reinhold Company, New York, 1978, pp.106-116.

AUDIO-VISUAL MATERIALS FOR LESSON 5

Lesson 5 Settling Chamber--Principles, Operation and Applications

413-5-1	Simple settling chamber
413-5-2	Collection mechanisms
413-5-3	Settling chamber
413-5-4	Howard settling chamber
413-5-5	Baffle chamber
413-5-6	Particle behavior in a settling chamber
413-5-7	Theoretical efficiency
413-5-8	Stokes law
413-5-9	Determining minimum particle size
413-5-10	Efficiency formula
413-5-11	Process design parameters

CONTENT OUTLINE

Course: 413 - Lesson 5
Lecture Title: SETTLING CHAMBER PRINCIPLES

Page 1 *of* 5

NOTES

I. Introduction

Settling Chambers - used in industry to remove large solids and liquid waste from gas streams. Composed of very simple design, low cost and maintenance, low pressure losses, and simple disposal of collected materials -- *used generally as precleaner, spark arrestors and sometimes used to cool down exhaust gases.

Slide: 413 - 5-1

II. Collection mechanisms -- 2 main simple mechanisms -- gravity and inertia.

A. Gravity -- Particle velocity reduced to such an extent that particle will settle out under action of gravity. Separation provided free by nature -- generally limited by particles > 40 microns in size.

Slide: 413 - 5-2

B. Inertial forces -- or momentum effect. In addition to gravity successful separation depends on inertial or momentum effect. This occurs by changing the direction of the velocity of the gas and imparting a downward motion to the particle.

III. Two types of gravity settler

Slide: 413 - 5-3

A. Simple expansion chamber -- consists long parallel box with suitable inlets and outlet parts -- gas enters one end, larger particles settle out due to gravity forces, gas exits other end. Velocity of gas slowed down due to expansion in chambers, enabling particles to fall out due to gravity.

B. Another type of gravity settler is called a Howard Settling Chamber.

Slide: 413 - 5-4

- consists of several thin horizontal collection plates, to reduce the excessive volume requirements to collect particles.
- vertically distance for collection has decreased (may be as little as 1 inch).
- uniform distribution of gas is achieved by use of guide vanes, distributor screens, or perforated plates. One problem with Howard Settling Chamber is cleaning, and also warping of trays possible when gas temperature high.

IV. **Momentum separators**

Use inertial or momentum forces in addition to gravity to collect particles. Particules down to 10-20 μ can be collected. Physical arrangement involves use of baffle. Pressure losses .1 to 1 in H_2O.

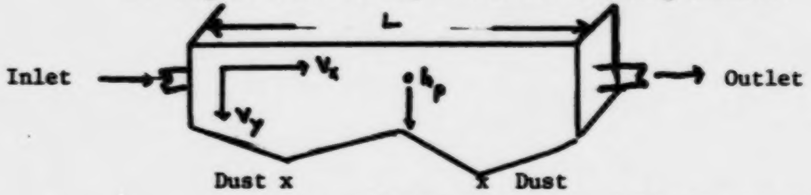
Slide: 413 - 5-5

V. **Particle velocity**

Understanding the principles of collection in a gravity settler begins with examining the behavior of a single spherical particle.

Looking at a box to represent the settling chamber:

Slide: 413 - 5-6



h_p = distance particle falls for capture
v_x = horizontal velocity of gas
v_y = vertical velocity of particle

let t_r = residence time assume v_x particle velocity is equal to gas velocity ①

Note: See 413 Manual p.3-13 to 3-17 for derivation

$$t_r = \frac{L}{v_x} \quad \text{or} \quad t_r = \frac{LBH}{Q} \qquad v_x - \frac{Q}{BH} \qquad ②$$

Q = gas flow rate
H = height of chamber
B = width of chamber

let t_s = time required for particle to settle

$$t_s = \frac{H}{v_t} \quad \begin{matrix} \text{- distance} \\ \text{- terminal velocity} \end{matrix} \qquad ③$$

(same as v_y)

for captive $t_s < t_r$

in the limit

$$t_s = t_r$$

$$H/v_t = \frac{LBH}{Q}$$

$$v_t = \frac{Q}{LB} \qquad ④$$

VI. Particle Settling Theory -- Efficiency

Now expressing the efficiency of the unit

$$\eta = \frac{v_y L}{v_x H} \times 100\%$$

Theoretical efficiency (3.2.9 in book)

Slide: 413 - 5-7

NOTE: 3.2.9 in book The assumption here is that the flow through the settling chamber is laminar, but that is not always the case. This is the theoretical efficiency.

η = fractional efficiency of particles size d_p (one size)

v_y = vertical settling velocity

v_x = horizontal gas velocity

L = chamber length

H = distance particle must settle to be collected -- Chamber Height

Now, we had seen that the settling velocity given from Stokes Law previously discussed as:

$$v_t = \frac{g\, d_p^2\, (\rho_p - \rho)}{18\mu}$$

3.2.6 in manual

Slide: 413 - 5-8

Where v_t = settling velocity

g = acceleration due to gravity

d_p = particle diameter

ρ_p = density of particle

ρ = density of gas

μ = gas viscosity

* Remember v_t applicable for Re# $\leq$ 1.9

and

$$d_p^* = \left(\frac{18\, \mu\, Q}{g \rho_p BL}\right)^{1/2}$$

3.2.7 in manual

where $v_t = \frac{Q}{LB}$

Slide: 413 - 5-9

NOTE: Equation 3.2.7 assumes that 100% collection efficiency of size d_p will occur. However, Stokes law does not always apply and this equation can yield some errors.

d_p* - represents the limiting value since particles equal to or greater than the value will reach the collection surface

* NOTE: $(\rho_p - \rho)$ reduces to ρ_p because

$$\rho_p >> \rho$$

particle density gas density

Now we can state the efficiency

$$\eta = K\left[\frac{g\ (\rho_p - \rho)\ L\ B\ N_c}{18\ \mu\ Q}\right] d_p^{\,2}$$

3.2.10 note brackets

where term in brackets is constant and is multiplied by K which is an empirical factor (usually .5) when test information is not available

Factors (1) all particles do not have free fall
(2) agglomeration during settling changes particle size
(3) some particles are re-entrained

VII. Equation for determining the effiency for a settling chamber - Turbulent Flow

1. The flow through a settling chamber is almost always turbulent.
2. The equation for efficiency is thus given by:

$$\eta = 1 - \exp\left[\frac{-L\ V_t}{H\ V_x}\right]$$

where η = efficiency
L = length of chamber
H = height particle must fall (chamber height)
V_t = settling velocity
V_x = horizontal gas velocity

Slide: 413 - 5-10
NOTE: N_c = # of parallel chambers

VIII. Process — Design parameters

Slide: 413 - 5-11

1. Length -
2. Width -
3. Height -

{ usually designed by industry to remove all particles above a specified particle size $d_p{}^*$

4. Volume - (which involves above 1, 2, & 3) Should be that sufficient residence time for volume rate gas treated is provided for capture of all particles of designed size
5. Through-put velocity - rule of thumb below 10 ft/sec
6. Through-put velocity should not exceed pick up velocity given in Table 3.2.1.

IX. Review

The past 45 minutes we've talked about:

* collection mechanisms
* two types of settling chambers
* Stokes law for determining the settling velocity of a particle
* The equation to determine the minimum particle size collected in a settling chamber
* The equation to calculate the collection efficiency of a settling chamber
* The system design parameters used in designing settling chambers

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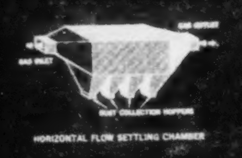
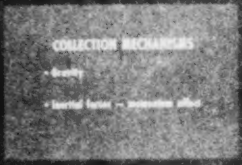

GAS OUTLET
GAS INLET
DUST COLLECTION HOPPERS

HORIZONTAL FLOW SETTLING CHAMBER

1



COLLECTION MECHANISMS

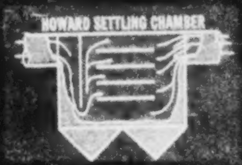
- Gravity
- Inertial forces — momentum effect

2

GAS OUTLET
GAS INLET
DUST COLLECTION HOPPERS

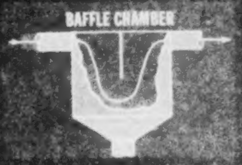
HORIZONTAL FLOW SETTLING CHAMBER

3



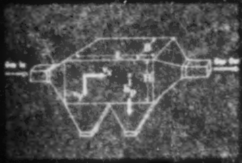
HOWARD SETTLING CHAMBER

4

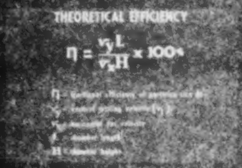


BAFFLE CHAMBER

5


Gas In
Gas Out
L
B
H
v_x
v_y
h_p

6

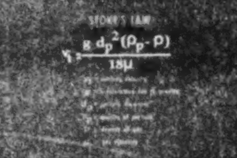


THEORETICAL EFFICIENCY

$$\eta = \frac{v_y L}{v_x H} \times 100\%$$

η — [illegible]
v_y — [illegible]
v_x — [illegible]
L — [illegible]
H — [illegible]

7

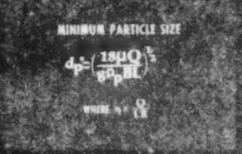


STOKE'S LAW

$$v_t = \frac{g\, d_p^2(\rho_p - \rho)}{18\mu}$$

[illegible]

8

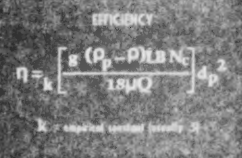


MINIMUM PARTICLE SIZE

$$d_p = \left(\frac{18\mu Q}{g\rho_p BL}\right)^{1/2}$$

WHERE $v_t = \frac{Q}{LB}$

9

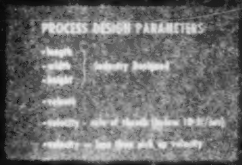


EFFICIENCY

$$\eta = k\left[\frac{g\,(\rho_p - \rho)LB N_c}{18\mu Q}\right]d_p^2$$

k = empirical constant (usually .5)

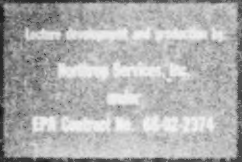
10



PROCESS DESIGN PARAMETERS

- length
- width } industry designed
- height
- volume
- velocity - rule of thumb (below 10 ft/sec)
- velocity — less than pick up velocity

11



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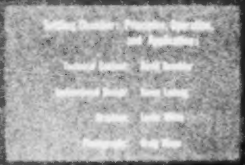

Settling Chamber: Principles, Operation, and Applications

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Instructional Design: [illegible]
Graphics: [illegible]
Photography: [illegible]

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LESSON PLAN

AIR POLLUTION TRAINING INSTITUTE

TOPIC: PROBLEM SESSION III
SETTLING CHAMBERS

COURSE: 413 - Lesson 5a
LESSON TIME: 15 minutes
PREPARED BY: D. Beachler DATE: 6/79

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

LESSON GOAL: Briefly describe the use of the settling velocity and efficiency equations covered in the previous lecture by solving two short problems.

SUPPORT MATERIALS AND EQUIPMENT:

(1) chalk board
(2) 413 Student Workbook pp. 8-9

CONTENT OUTLINE

Course: 413 - Lesson 5a
Lecture Title: SETTLING CHAMBERS - PROBLEM SESSION [illegible]

Page 1 *of* 2

NOTES

I. Problem 3-1

A. Have students turn to page 8 in the 413 Student Workbook and begin working the problem 3-1.

B. Allow students 5 minutes to work problem then go over the solution.

The solution to problem 3-1 is:

Note: See page 8 in 413 in Student Workbook

3.1 Settling Chamber — Minimum Particle Size

A hydrocholoric acid mist in air at 25°C is to be collected in a gravity settler. The unit is 30 ft wide, 20 ft high, and 50 ft long. The actual volumetric flow rate of the "acidic" gas is 50 ft^3/sec. Calculate the smallest mist droplet (spherical in shape) that will be entirely collected by the settler. The specific gravity of the acid is equal to 1.6. Assume the acid concentration to be uniform through the inlet cross section of the unit.

Assume Stoke's Law applies and at 25°C $\mu = 0.0185$ cp,

$$1 \text{ cp} = 6.72 \times 10^{-4} \frac{\text{lb}}{\text{ft-sec}}$$

SOLUTION:

The important data are tabulated below:

$T = 25^{\circ}C$
$B = 30$ ft
$H = 20$ ft
$L = 50$ ft
$Q = 50\ ft^3/sec$
$\rho = 1.6$

(1) at 25°C

$$\mu = .0185 \text{ cp} \times 6.72 \times 10^{-4} \frac{\text{lb}}{\text{ft-sec}} \Big/ \text{cp}$$

$$= 1.24 \times 10^{-5} \frac{\text{lb}}{\text{ft-sec}}$$

(2) The describing equation (since Stokes law applies)

$$d_{p(min)} = \left[\frac{18\mu Q}{g\,\rho_p\,BL}\right]^{\frac{1}{2}}$$

$$d_p = \left[\frac{(18)(1.24 \times 10^{-5} \frac{\text{lb}}{\text{ft-sec}})\left(50 \frac{ft^3}{sec}\right)}{(32.2 \frac{ft}{sec^2})(1.6) \times 62.4 \frac{lb}{ft^3}(30\text{ ft})(50\text{ ft})}\right]^{\frac{1}{2}}$$

spec Gravity of air or H_2O 1.0 ∴ multiply by 62.4

$$d_p = 4.81 \times 10^{-5} \text{ ft}$$

II. Problem 3-2

A. Have students turn to page 9 in the 413 Student Workbook and begin working on problem 3-2.

B. Allow students 5 minutes to solve problem and then go over the solution.

The solution for problem 3-2 is:

Note: See page 9 in 413 Student Workbook.

3.2 Settling Chamber - Operating Efficiency

A gravity settler 5 meters wide, 10 meters long, and 2 meters high, is used to trap particles with diameters of 10 µm. The gas flow rate is 0.4 m^3/sec. Calculate the operating efficiency of a settling chamber for the data given below. Assume Stokes law regime and a Cunningham correction factor of 1.0.

$$\rho_p = 1.10 \text{ gm/cm}$$
$$\rho = 1.2 \times 10^{-3} \text{ gm/cm}$$
$$\mu = 1.8 \times 10^{-4} \frac{\text{gm}}{\text{cm - sec}}$$

SOLUTION:

$$\eta(d_p) = \left[\frac{g\ \rho_p\ BL\ N_c}{18\ \mu Q}\right] d_p{}^2$$

$$= \frac{980 \text{ cm/sec}^2 \times 1.10 \text{ gm/cm} \times 500 \text{ cm} \times 1000 \text{ cm} \times 1 \times \left(10\ \mu \times 1 \times 10^{-4} \frac{\text{cm}}{\mu}\right)^2}{18 \times 1.8 \times 10^{-4} \frac{\text{gm}}{\text{cm-sec}} \times 04 \frac{m^3}{\text{sec}} \times 10^6 \frac{\text{cm}^3}{m^3}}$$

$$= .415 \times 100\%$$

$$= 41.5\%$$

LESSON PLAN

AIR POLLUTION TRAINING INSTITUTE

TOPIC: CYCLONES: PRINCIPLES, OPERATION, AND APPLICATIONS

COURSE: 413 - Lesson 6
LESSON TIME: 45 minutes
PREPARED BY: **DATE:** 4/79
David S. Beachler

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

LESSON GOAL: Briefly describe the basic design and principles of a cyclone used for collection of particulate emissions.

LESSON OBJECTIVES: At the end of the lesson the student should be able to:

1. Briefly describe a simple cyclone for particle collection and describe how the gas stream and particles flow in a cyclone.
2. Name two mechanisms used for the collection of particles in a cyclone.
3. Describe the cut size and critical size of a particle.
4. Recognize the formula for cut size and calculate the cut size for a specific cyclone.
5. Calculate the pressure drop across the cyclone using the pressure drop equation.
6. Describe in general terms the physical features and mode of operation of multiple cyclones.
7. Calculate the collection efficiency of a cyclone using efficiency curves and particle size distribution data.
8. Recognize the sources where cyclones can and can't be used in industry to collect dust.

STUDENT PREREQUISITE SKILLS: Ability to understand basic principles of physical science

LEVEL OF INSTRUCTION: Advanced

INTENDED STUDENT PROFESSIONAL BACKGROUND: Engineering or Physical Science

SUPPORT MATERIALS
AND EQUIPMENT:

1. slide projector
2. overhead projector
3. chalkboard
4. 413 Student Manual

REFERENCES:

1. 413 Student Manual
2. 413 Student Workbook
3. "Air Pollution Control Technology, an Engineering Analysis Point of View," by Robert M. Bethea, Van Nostrand Reinhold Company, New York, 1978.
4. "New Design Approach Boosts Cyclone Efficiency," Chemical Engineering November 7, 1978, by Wolfgang H. Koch and William Licht. pp. 117-143
5. Leith, David and Mehta, Dilip, Cyclone Performance and Design Atmospheric Environment Vol 7, pp 527-549, 1973.

AUDIO-VISUAL MATERIALS FOR LESSON 6

Lesson 6 Cyclone Theory and Applications

413-6-1	Cyclone--live shot
413-6-2	Collection mechanisms
413-6-3	Cyclone--main parts
413-6-4	Simple cyclone--flow of gas
413-6-5	Cyclone with fines eductor
413-6-6	Critical size
413-6-7	Cut size
413-6-8	Cut size particle diameter equation
413-6-9	Size efficiency curve
413-6-10	Simple cyclone--typical dimensions
413-6-11	Pressure drop equation
413-6-12	Multiple cyclone
413-6-13	Cut size particle diameter equation

CONTENT OUTLINE

Course: 413 Lesson 6
Lecture Title: CYCLONE THEORY AND APPLICATIONS

NOTES

I. Introduction

A cyclone is known as a mechanical collector — a structure without moving parts -- that separates particulate matter from the gas stream.

413-6-1

II. Collection Mechanisms

The collection mechanisms used for collecting particles are 1. centrifugal force and 2. gravity

413-6-2

1. Centrifugal force -- outward force created by the cyclone arrangement -- particles are forced to the outside wall of the collector
2. Gravity -- once the particles reach the wall, the heavier particles are overcome by a gravitational force and fall to the bottom of the chamber

III. Description of cyclone

1. Inlet gas velocity is transformed (mechanically) into a vortex which is confined within a structure

   413-6-3

   (a) gas enters the cyclone tangentially

   (b) vortex spirals downward (main vortex) and near bottom of cone -- reverses in direction and spirals upward -- core vortex. Spiralling action of gases causes particles to be driven to the walls where they collect (on the surface) and move downward by force of gravity.

   413-6-4

   (c) Spiral motion of both vortexes spirals in the same direction. Tangential velocity (gas swirl spread) is lowest near the wall and at the center of the cyclone. It reaches the maximum approx. 60-70% in from the wall towards the center of cyclone.

   (d) Two opposing forces -- outward centrifugal force and inward drag force which is a function of the $[F_R = K_2 v d_p \mu]$density, particle shape and diameter; whenever centrifugal force > drag force, particles will reach walls and be collected.

NOTE: Centrifugal Force

$$F_s = \frac{\rho_p d_p^3 v_p^2}{gr}$$

(e) Vortex arrestor (is the hopper) at the bottom -- where the gases reverses bulk flow directions

NOTE: point out vortex arrestor

NOTE: point out vortex finder

Back mixing

(f) (1) Eddy currents (plagues efficiency) generate at top of unit where dirty gas is introduced. Turbulence of eddies causes some dirty gas to be mixed with clean gas. Problem can be partially eliminated by use of a vortex finder -- projects into body of cylinder.

(2) Also can add a fines eductor or skimmer -- bleeds out very fine particulates which tend to accumulate at top. The small purge stream of gas is re-introduced close to the wall just before start of the tapered section. Fines are fed into the wall where they are bombarded by other particles being thrown against the wall and ∴ increased efficiency.

413-6-5

(3) Particles have a tendency to bounce off cylinder wall back into inner vortex -- can be eliminated by water sprays along the sides of the cyclone. Walls should be smooth for good efficiency and low pressure drop.

(g) Inlets -- air inlets also play a major role in reducing eddy currents. Air is squeezed to about half of the inlet width to reduce the interference of the incoming gas and the vortex finder -- Helical and involute inlets are used *[see p. 4-10 in manual]. Also used are vanes (inlet vanes) called axial inlet. Vanes must resist erosion and plugging.

NOTE: turn to page 4-10 in manual

(h) Discharge Bin -- (can be a problem)
Since static pressure in core is slightly negative, the collected dust will be drawn up into vortex core to discharge to the atmosphere.

Solution is a mechanical device
(1) rotary valve
(2) double flap valve
(3) screw conveyer

The function of this device is for the continuous complete immediate dust removal and prevent inflow of air from hopper.

IV. Determination of critical particle size and cut size

When performing calculations for the efficiency of a cyclone we need to look at the critical size and cut size.

1. Two sizes used to relate to the efficiency of the cyclone. Their derivation is not presented here in the lecture. NOTE: They should not be used for original calculations, but rather to compare efficiencies of similar cyclones.
2. Critical particle size is defined as the size of the smallest particle which can be removed completely. 100% efficiency.

413-6-6

NOTE: Red particle on slide represents the particle of critical size.

3. Also a convenient way to define the efficiency is by use of the term cut size. It is the size of particle collected with 50% efficiency. The cut size depends on the gas and particle properties, the cyclone size and operating conditions

413-6-7

NOTE: Red particle on slide represents the particle of cut size.

$$[d_p]\text{ cut} = \left(\frac{9\ \mu\ B_c}{2\pi\ N_t\ v_i(\rho_p - \rho\ )}\right)^{\frac{1}{2}}$$

413-6-8 -

NOTE:
(Eq. 4.2.1 in Manual)

where $[d_p]$ cut = cut size

B_c = width of gas inlet (ft)

N_t = Number of revolution gas stream makes - (3-10) generally 5 (dimensionless) unless manufacturer states otherwise

NOTE:
N_t can be calculated
See pages 4-23 - 4-24 in 413 Manual

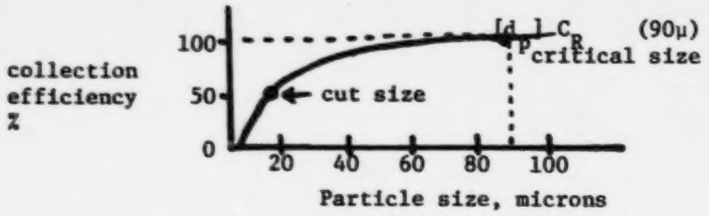
v_i = inlet velocity, ft/sec

ρ_p = particle density #/ft^3

ρ = gas density #/ft^3

4. Looking at a size-efficiency curve is a plot of different particle sizes related to removal efficiencies for a certain cyclone

413-6-9



Size efficiency curve

Point out
1. cut size
2. critical size

IV. Relative Dimensions

413-6-10

Several dimensional proportions are used in a cyclone design (see slide) (See example in book 4.2.1, 4.2.2, 4.2.3)

1. Usually start out specifying body diameter D
2. Dimensional proportions
   (a) height to width of inlet
   (b) vortex finder diameter to cyclone body diameter
   (c) body diameter to vortex arrestor diameter
   (d) length of cylindrial body to tapered section
   (e) length of vortex finder to body diameter and inlet height.

Point out in manual 4.2.1, 4.2.2, 4.2.3

*3. *Principal dimension is the body diameter because it governs capacity of the cyclone at a reasonable pressure drop.
4. The overall length determines the # of turns gas makes
5. The inlet dimension determines the velocity and thus centrifugal force applied to the particles.
6. Note these and other dimensions are fixed by the designer in accordance with particle collection requirements and volume of gas handled.

NOTE:
(B_c is real important See IV-3)

V. Pressure Drop Determination

1. Pressure drop across a cyclone varies from 1 to 7 inches of water

2. An equation does exist for computing pressure drop -- for several conditions. For geometrically similar cyclones.

413-6-11

$$\Delta p = \frac{.0027\ Q^2}{k\ D_e^2\ B_c H_c (L_c/D_c)^{1/3} \left[\frac{Z_c}{D_c}\right]^{1/3}}$$

* equation 4.2.7 in manual

where:

Δp = pressure drop, in H_2O
Q = volumetric flow rate at the inlet, ft^3/sec
D_e = diameter of gas outlet, ft
B_c = inlet width, ft
H_c = inlet height, ft
L_c = height of cylinder, ft
D_c = cyclone diameter, ft
Z_c = height of cone, ft (tapered section)
k = diamensionless factor descriptive of cyclone inlet vanes - 0.5 without vanes, 1 for vanes that do not expand the entering gas or touch the gas outlet wall (a in Figure 4.2.12), and 2.0 for vanes that expand and touch the gas outlet wall (b in Figure 4.2.12).

Remember that the cyclone dimensions (B_c, H_c, etc.) are the inner dimensions. For example, B_c is the inside width of the duct, not including any lining, etc.

(Figure 4.2.12)

VI. Types and arrangements of cyclones

1. Individual high efficiency cyclone must be small in diameter and have a small capacity -- thus they are operated in parallel multiples to handle typical gas volumes. Battery has common inlet chamber (plenum), common outlet plenum, and common dust collection system. Chambers must be designed for constant ΔP in each

cyclone to avoid channeling of dirty gases to any one cyclone or group (least resistance effect.)

2. Multicyclone (vane axial cyclone) — 413-6-12
   - (a) common gas inlet
     gas outlet
     hopper
   - (b) virtually no eddies and loss of fines because there is no tangential or involute entrance.
   - (c) pressure drop in multicyclones is 4-6 in H_2O.
   - (d) should not be used for hygroscopic or other "sticky" materials because vanes would plug up causing pressure drop problems.
3. Cyclones in series
   - (a) additional pressure drop makes series arrangement a disadvantage.
   - (b) single large cyclones may be used as a precleaner for multiple cyclones to prevent them from plugging.

VII. Determination of Overall Efficiency

1. To predict the overall efficiency (collection). The size-efficiency curve and a particle size distribution are required.
2. Note that the size efficiency curve applies to that designed cyclone collecting a certain type dust and would only apply to a cyclone with similar gas and particulate conditions.
3. Method for determining efficiency — Work problem 4.1 in workbook 413-6-13
   - (a) determine $[d_p]$ cut
     - (1) can do by equation $[d_p]$ cut
     - (2) * Lapple's technique -- using Figure 4.2.4 p. 4-20 conventional cyclone — See figures 4.2.4 and 4.2.5 in 413 manual
       * For other conditions multiply $[d_p]$ cut by correction factors 4.2.5, 4.2.6
   - (b) Use a size efficiency curve
     - (1) cyclone efficiency vs. particle size ratio -- Lapple 1951. Using a graph like 4.2.7 — See figures 4.2.7 in 413 manual
       * Particle size as a function of the particle size ratio.

(2) Particle size distribution
Divide the particle-size distribution of the dust to be collected into ranges OR can use a curve like figure 4.2.8 -- "Typical Particle Size Distribution"

See figure 4.2.8 in 413 manual

(c) Multiply the weight fraction for each size range by the collection efficiency determined (above). The summation gives the overall collection efficiency.

VIII. Cyclone performance - other methods for efficiency determination

1. The following information was taken from a paper written by David Leith and Dillip Mehta (see reference listing).

NOTE: This section is optional and can be included in this lesson.

CYCLONE COLLECTION EFFICIENCY

Cyclone fractional efficiency is the weight of particles of a stated size collected in the cyclone, divided by the total weight of particles of that size going to the cyclone. Experience in dealing with cyclones has shown that collection efficiency increases with:

(1) Increasing particle size and density.
(2) Increasing speed of rotation in the cyclone vortex.
(3) Decreasing cyclone diameter.
(4) Increasing cyclone length
(5) Drawing some of the gas from the cyclone through the dust exit duct.
(6) Wetting the cyclone's walls.

A cyclone's grade efficiency curve relates size of particles going to the cyclone to the cyclone's efficiency on particles of that size. Note that efficiency continuously increases with increasing particle diameter, and approaches 100 per cent asymptotically for sufficiently large particles.

Critical size approach to cyclone efficiency

The efficiency of a cyclone is sometimes characterized by its particle "critical size" (the size of particles calculated to be collected with 100 per cent efficiency), or by its "cut size" (the size of particles calculated with 50 per cent efficiency). As discussed above, actual collection efficiency approaches 100 per cent asymptotically for larger particles. The critical size particle then, while calculable from theory, is not observed experimentally.

2. Leith has given an equation to calculate the efficiency of a cyclone:

$$\eta = 1 - \exp\left[-2(C\Psi)^{1/(2n+2)}\right]$$

The terms in this equation are C
Which can be calculated or picked from a table for standard design cyclones; Ψ is a term for the inertial impaction parameter and given by

$$\Psi = \frac{\rho_p d_p^2 v_g}{18 \mu_G D} (n + 1)$$

and the value of n can be picked from a single figure and depends on cyclone diameter and gas temperature.

IX. Applications

1. Cyclones generally used to collect larger particles (> 20 microns in size). Multicyclones can collect down to 5-10 microns in size.
2. Sometimes used as pre-cleaners to a baghouse, ESP or scrubber.

3. Cyclone pressure drops vary depending on the size and the design.
   a. low efficiency cyclones - 2-4 inches of water
   b. medium efficiency cyclones - 4-6 inches of water
   c. high efficiency cyclones - 8-10 inches of water
   d. multicyclones - 4-6 inches of water

4. Cyclone sizes vary depending on their use and design.
   a. 5000 - 10,000 CFM per unit (up to six in a group) for cyclones.
   b. 25,000 -100,000 CFM for multicyclones.

5. Cyclones can be used in various industries such as iron and steel, asphalt, grain milling, cement, paper, chemical, coal cleaning, etc. The efficiency of the collectors will be dependent on the particles being handled, the gas volume and the size of the unit. Table 4.3.1 on page 4-34 of the manual lists various cyclone applications in industry.

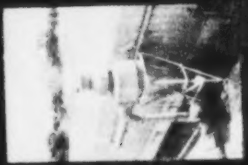
X. Review

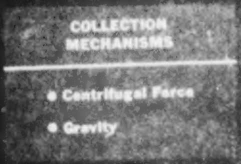
We have discussed the past hour the following subjects:

- * collection mechanisms involved for particle capture
- * basic operation of the cyclone including the
  - inlet
  - vortex spiral
  - vortex arrestor
  - vortex finder
  - discharge bin
- * defined the cut size and the critical size
- * the equation used to calculate the cut size
- * the equation used to calculate the pressure drop across a cyclone
- * cyclone collection efficiency using efficiency curves and particle size distribution data.

NSERT FILM EMULSION SIDE DOWN

DATE 6/80 ASSIGNMENT 413 L-6 NO 6

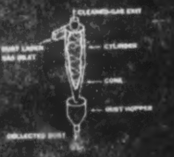


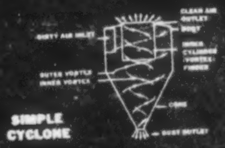


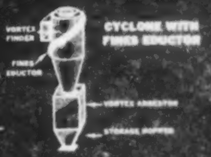
COLLECTION MECHANISMS

- Centrifugal Force
- Gravity

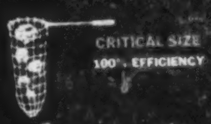
2

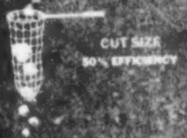

CLEANED-GAS EXIT
DUST LADEN GAS INLET
CYLINDER
CONE
DUST HOPPER
COLLECTED DUST

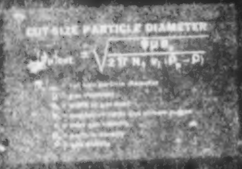

SIMPLE CYCLONE
DIRTY AIR INLET
CLEAN AIR OUTLET
DUST
INNER CYLINDER (VORTEX) FINDER
OUTER VORTEX
INNER VORTEX
CONE
DUST OUTLET


CYCLONE WITH FINES EDUCTOR
VORTEX FINDER
FINES EDUCTOR
VORTEX ARRESTOR
STORAGE HOPPER

5

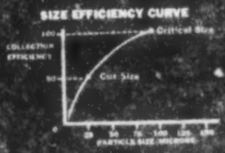

CRITICAL SIZE
100% EFFICIENCY


CUT SIZE
50% EFFICIENCY

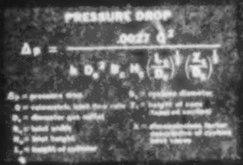


CUT SIZE PARTICLE DIAMETER

$$(d_p)_{cut} = \sqrt{\frac{9\mu B_c}{2\pi N_t v_i (\rho_p - \rho)}}$$



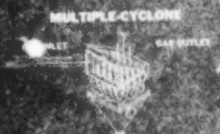
SIMPLE CYCLONE

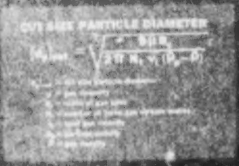


PRESSURE DROP

$$\Delta p = \frac{.0027\,Q^2}{k\,D_e^2\,B_c\,H_c\left(\frac{L_c}{D_c}\right)^{\frac{1}{3}}\left(\frac{Z_c}{D_c}\right)^{\frac{1}{3}}}$$

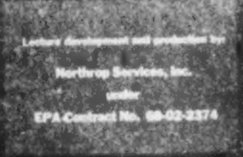
11


MULTIPLE-CYCLONE
INLET
GAS OUTLET



CUT SIZE PARTICLE DIAMETER

$$(d_p)_{cut} = \sqrt{\frac{9\mu B_c}{2\pi N_t v_i (\rho_p - \rho)}}$$



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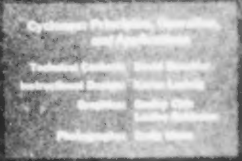


Cyclones: Principles, Operation, and Applications

LESSON PLAN

AIR POLLUTION TRAINING INSTITUTE

TOPIC: PROBLEM SESSION IV
CYCLONES

COURSE: 413 - Lesson 6a
LESSON TIME: 45 minutes
PREPARED BY: DATE: 6/79
David S. Beachler

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

LESSON GOAL: Briefly describe the use of the cut size determination, pressure drop, and collection efficiency equations covered in the previous lecture by solving four problems.

SUPPORT MATERIALS AND EQUIPMENT:

1. Chalkboard
2. 413 Student Workbook pp. 10-16

CONTENT OUTLINE

Course: 413 - Lesson 6a
Lecture Title: CYCLONES - PROBLEM SESSION IV

Page 1 of 13

NOTES

I. Problem 4-1

A. Work out problem 4-1 for the students. The solution for 4-1 is:

See attached sheets

NOTE:
See problems 4-1 on page 10 of the 413 Student Workbook.

4.1 Cyclone — Overall Collection Efficiency Using Lapple's Method

The particle size distribution of a dust from a cement kiln is provided below:

Particle Size (Average size in range) microns	% Wt
1	3
5	20
10	15
20	20
30	16
40	10
50	6
60	3
> 60	7

The following information is also known:

Gas Viscosity	0.02 centipoise (cp)
Particle Specific Gravity	2.9
Inlet Gas Velocity to Cyclone	50 ft/sec
Effective Number of Turns within Cyclone	5
Cyclone Diameter	10 ft
Cyclone Inlet Width	2.5 ft

(a) Determine the cut size particle diameter, i.e., diameter of particle collected at 50% efficiency, and estimate the overall collection efficiency using Lapple's Method.

(b) If the same cyclone is used, but the inlet gas velocity is increased to 60 ft/sec and the gas viscosity changes to 0.018 cp due to a temperature decrease (all else remaining the same), find the new cut size particle diameter and determine the new overall collection efficiency using Lapple's Method.

SOLUTION:

(a)
$$d_{p\ cut} = \left[\frac{9\ \mu\ B_c}{2\ N_t\ v_i\ (\rho_p-\rho)\ \pi}\right]^{1/2}$$

$$= \left[\frac{9 \times (.02_{cp} \times 6.72 \times 10^{-4}\,\frac{lb}{sec\ ft}) \times 2.5}{2 \times (5) \times 50\,\frac{ft}{sec} \times (2.9 \times 62.4\,\frac{lb}{ft^3})\ (\pi)}\right]^{.5}$$

$$= 3.2 \times 10^{-5}\ ft \times 30.48 \times 10^{4}\ \mu m/ft.$$

Note: ρ gas much less than ρ_p $\therefore$ $\rho_p - \rho = \rho_p$

$$= 9.9\ \mu m$$

4.1 (a) cont'd

Alternatively Lapple provides a curve to determine the cut size particle diameter Figure 4.2.4 in the manual. From Figure 4.2.4 d_p cut is approximately 9.9 (NOTE: one must project graph to be able to read out size for a 10 ft diameter cyclone).

construct table

d_p microns	wt%	d_p/dp cut	η % from Figure 4.2.7	wt fraction % x η%
1	3	.0101	nil	0
5	20	.505	20%	.040
10	15	1.01	50%	.075
20	20	2.02	80%	.160
30	16	3.03	90%	.144
40	10	4.04	94%	.094
50	6	5.05	97%	.058
60	3	6.06	99%	.030
760	7	----	100%	.07
				.671

Collection efficiency = 67%

4.1 (b) Since inlet conditions have varied, it is necessary to apply the correction factors to the particle cut size diameter previously determined

Inlet velocity correction (from 4.2.5)

= .92

Viocosity correction (from 4.2.5)

= .95

Corrected cut size = $(d_p)_{cut}$ (.92)(.95)

= 9.02

4.1 (b) cont'd

d_p	wt %	d_p / d_p cut (new)	η% (from) (4.2.7)		Wt fraction x η %
1	3	.111	----		0.0
5	20	.554	24	(.20)(.24) =	0.048
10	15	.90	45		.0675
20	20	2.22	83		.167
30	16	3.33	91		.146
40	10	4.43	94		.094
50	6	5.54	96		.058
60	3	6.65	98		.029
760	7	----	100		.07
					.680

New overall collection efficiency is approximately 68%

II. Problem 4-2

A. Work out problem 4-2 for the students. The solution for 4-2 is:

NOTE: See problem 4-2 on page 11 of the 413 Student Workbook

4.2 Cyclone — Dimensions and Number of New Cyclones Required

A large-diameter conventional cyclone (no vanes) handles 5,000 ACFM of a particulate-laden gas exhaust stream (ρ_G = 0.076 lb/ft^3) from a certain metallurgical operation. The cyclone diameter is 4 ft. The remaining dimensions may be found from Figure 4.2.1 (in the manual). In an attempt to increase efficiency, a group of new cyclones is to be designed with the same geometrical proportions and pressure drop as the single cyclone. If the diameter of the small cyclone is to be 6 in., what will the dimensions of the new group be? How many cyclones will be needed to handle the original flow rate at the same pressure drop?

SOLUTION: Cyclone Dimensions (ft) - ?

	OLD	Dimension	New
From	4	D_c	.5
4.2.1	1	B_c	.125
	2	H_c	.25
	2	D_e	.25
	8	L_c	1.0
	8	Z_c	1.0

$$\Delta p_{\text{old}} = \frac{.0027\ Q^2}{k\ D_e^2\ B_c H_c\ (Z_c/D_c)^{1/3}}$$

k = .5 No vanes

$$\Delta p = \frac{(.0027)\left(\frac{5000\ \text{ACFM}}{60\text{sec/min}}\right)^2}{(.5)(2)^2(1)(2)\left(\frac{8}{4}\right)^{1/3}\left(\frac{8}{4}\right)^{1/3}}$$

$$= 2.95 \text{ in } H_2O$$

4.2 cont'd

$$\Delta p_{new} = 2.95 = \frac{.0027\ (Q)^2}{(.5)(.25)^2(.125)(.25)\left(\frac{1}{.5}\right)^{1/3}\left(\frac{1}{.5}\right)^{1/3}}$$

$$Q^2 = 1.7$$

$$Q = 1.3\ ft^3/sec \text{ per new 6" tube}$$

$$n = \frac{5000\ ACFM}{60\ sec/min} \Big/ \frac{ft^3/sec}{1.3\ tube} = 64 \text{ number of tubes}$$

Note that the inlet velocities for the old and new cyclones will be exactly the same.

$$(V_i)\ old = 83.3 \Big/ \underset{\overset{\uparrow}{B_c}}{(1)}\underset{\overset{\uparrow}{H_c}}{(2)} = 41.6\ \frac{ft}{sec}$$

$$(v_i)\ new = 1.3 \Big/ \underset{\overset{\uparrow}{B_c}}{(.125)}\underset{\overset{\uparrow}{H_c}}{(.25)} = 41.6\ \frac{ft}{sec}$$

III. Problem 4-3

A. Have students turn to page 12 in the 413 Student Workbook and begin working problem 4-3.

B. Allow students 10 minutes to work the problem; and then go over the solution.

The solution to problem 4-3 is:

(See next 2 pages)

NOTE: See problem 4-3 on page 12 of the 413 Student Workbook

4.3 Cyclone — Overall Collection Efficiency

(a) The size, mass, and cyclone collection efficiency data for a gas containing limestone dust are given below.

Particle diameter, μm	Wt %	Collection efficiency, %
0-5	2	4
5-10	8	6
10-20	13	20
20-30	26	32
30-50	12	78
50-75	11	89
75-100	9	95
100-200	8	98
200-	11	99+

Calculate the overall collection efficiency of the unit.

SOLUTION: is given by the product of the weight fraction and the collection efficiency for each size range. The following table provides the results.

d_p μm	Weight fraction	η %	(weight fraction)(η %)	
0- 5	.02	4	(.02)(4%) =	.08
5-10	.08	6	(.08)(6%)	.48
10-20	.13	20		2.60
20-30	.26	32		8.32
30-50	.12	78		9.36
50-75	.11	89		9.79
75-100	.09	95		8.55
100-200	.08	98		7.84
200-	.11	99		10.89
				57.91%

4.3 Cyclone — Mass of Dust Collected
(b) **If the inlet dust loading in the previous problem is 2.2 grains/ft^3 and the quantity of gas processed is 150,000 ACFM, calculate the mass of limestone collected daily.**

SOLUTION: Since the grain loading is 2.2 grains/ft^3, the mass collected per cubic foot of air is given by

$$\underset{\substack{\uparrow \\ \text{efficiency}}}{(2.2)(.58)} = 1.28\ \text{grains}/_{\text{ACFM}}$$

Daily mass collected is

$$150{,}000\ \text{ACFM} \times 1.28\ \frac{\text{grains}}{\text{ACFM}} \times 60\ \frac{\text{min}}{\text{hr}} \times 24\ \frac{\text{hr}}{\text{day}} = 276{,}480{,}000\ \frac{\text{grains}}{\text{day}}$$

$$\frac{2.76 \times 10^8}{7000\ \text{grains/lb}} = 39{,}497\ \text{lb/day}$$

limestone collected

IV. Problem 4-4

A. If time permits, have students turn to problem 4-4 on page 14 of the 413 Student Workbook and begin solving for the collection efficiency.

B. Allow students 10 minutes to solve problem 4-4; then go over the solution.

The solution for problem 4-4 is:

(See next 4 pages)

NOTE:
See problem 4-4
on page 14 of the
413 Student Workboo

4.4 Cyclone Collection Efficiency

Determine loss and collection efficiency for a cyclone from the following information.

(1) size-efficiency curve

(2) size distribution by weight

Particle size Micron	% by Wt Less than
10	.1
15	1.0
26	10.0
40	32.0
67	70.0
100	90.0
+100	100.0

(3) weight of inlet loading - 50 lb/hr.

4.4

SOLUTION

Using the size efficiency curve provided and data given, the following table can be constructed:

Particle Size Range	Mean Particle Size in range	Size Efficiency Curve % collected	% by Weight Within range	Inlet $\frac{\text{lb}}{\text{hr.}}$	Outlet $\frac{\text{lb}}{\text{hr.}}$
0 - 10	5	28	.1	(.1%)(50)= .05	(.72)(.05)= .036
10 - 15	12.5	52	.9	.45	.22
15 - 26	20.5	68	9.0	4.5	1.44
26 - 40	33	82	22.0	11.0	2.00
40 - 67	53.5	93	38.0	19.0	1.65
67 -100	83.5	99	20.0	10.0	.1
> 100		100	10.0	5.0	0
				50.00	5.44

$$\text{AEfficiency} = \frac{\text{inlet - outlet}}{\text{inlet}} \times 100\%$$

$$= \frac{50 - 5.44 \times 100}{50}$$

$$= 89\%$$

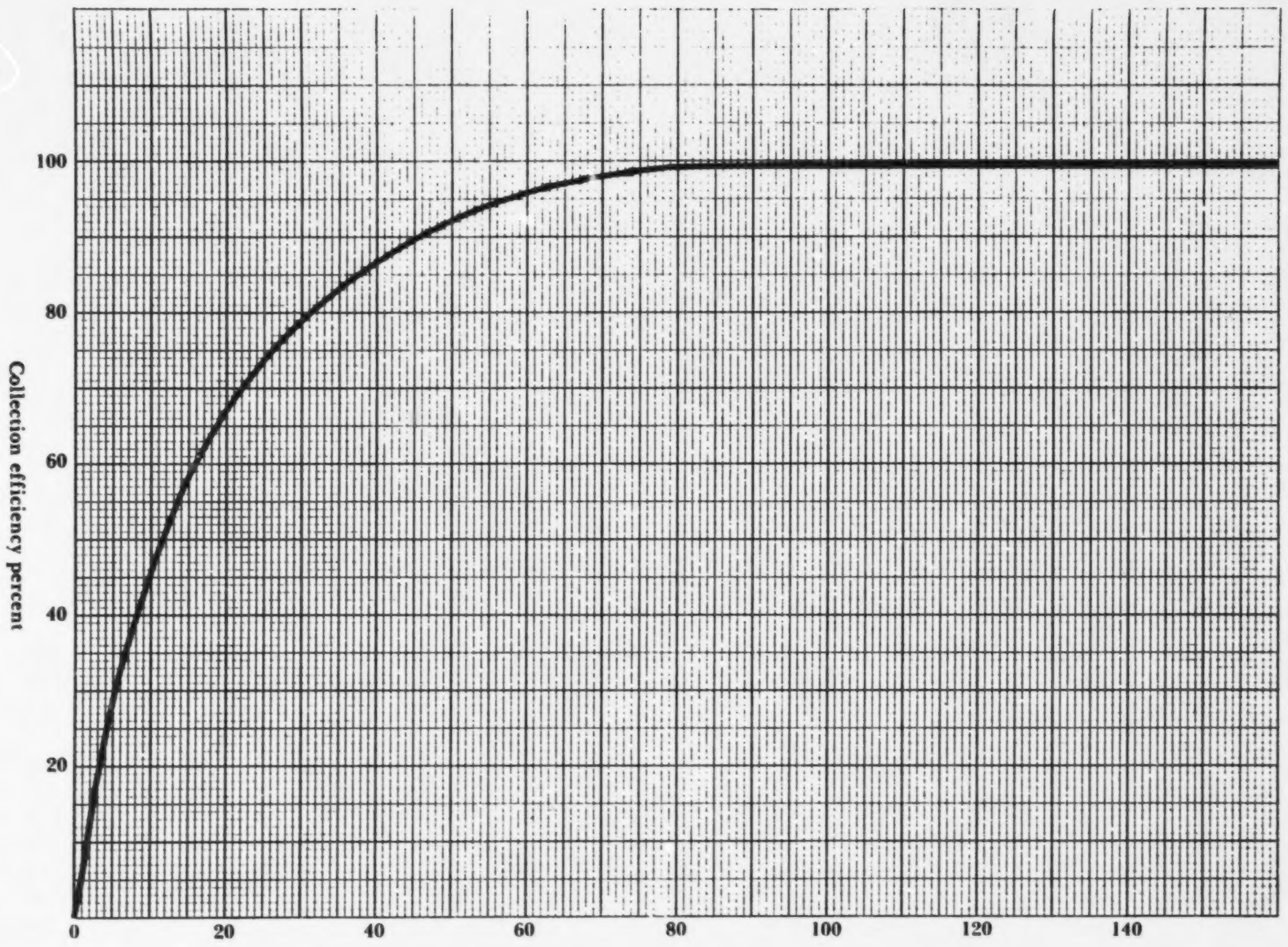
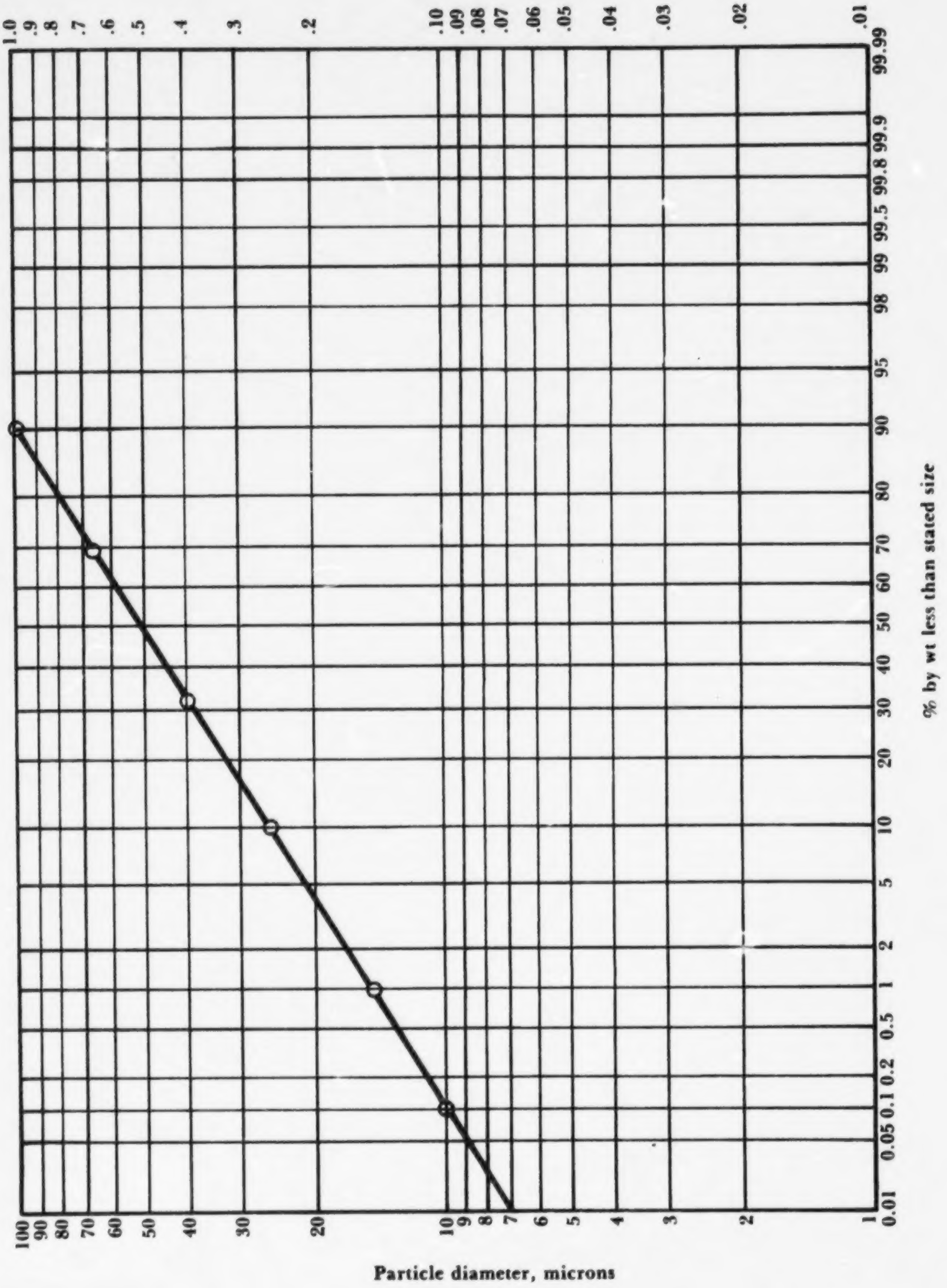


Figure 1. Particle size, microns size-efficiency curve for medium-efficiency high throughput cyclone


1.0
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0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.5
99.8
99.9
99.99
% by wt less than stated size
Particle diameter, microns

Figure 2.

LESSON PLAN

AIR POLLUTION TRAINING INSTITUTE

TOPIC: ELECTROSTATIC PRECIPITATOR PRINCIPLES AND OPERATION

COURSE: 413 - Lesson 7
LESSON TIME: 1 hour 15 minutes
PREPARED BY: DATE:
G. J. Aldina
Revised by David Beachler 2/21/80

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

LESSON GOAL: To familiarize the student with the basic theory of electrostatic precipitation of particles and the fundamental design considerations for building an ESP.

LESSON OBJECTIVES: The student should be able to:

1. List three structural components of an ESP
2. List three different types of ESP's
3. Identify the three basic functions of an electrostatic precipitator.
4. Describe each of the following basic mechanisms of the electrostatic precipitation process:
   - Gas ionization by corona discharge
   - Particle charging
   - Particle migration to the collection electrode
   - Loss of the particle electric charge at the collection electrode
   - Electric wind
5. Describe the ESP collection electrode cleaning process
6. Write an equation for ESP efficiency calculations
7. List the advantages of the ESP that make it a desirable control device.

SPECIAL INSTRUCTIONS: This lecture is intended to introduce the student to principles and operation of an electrostatic precipitator. The intent of this lecture is to focus on how the precipitator charges the particles and their subsequent collection at the collection plate.

In the following lecture, "Design and Applications", the intent will be to cover the finer design aspects of the ESP. The focus will be on typical design parameters, particle resistivity, common operating problems, operation and maintenance techniques and some applications of ESP's used for control of particulate emissions.

REFERENCES:

1. 413 Student Manual
2. Nichols, G. B., Seminar on ESP Theory
3. Gothchlich, C. F., Removal of Particulate Matter from Gaseous Wastes, American Petroleum Inst., N. Y., N. Y., 1961, Report on ESP
4. 413 Student Workbook

AUDIO-VISUAL MATERIALS FOR LESSON 7

Lesson 7 Electrostatic Precipitator Principles and Operation

413-7-1	ESP live shot
413-7-2	ESP schematic
413-7-3	Types of ESP
413-7-4	ESP schematic--single stage
413-7-5	Types of ESP
413-7-6	ESP--two stage
413-7-7	Types of ESP
413-7-8	ESP--water walled
413-7-9	Functions of an ESP
413-7-10	Discharge wire
413-7-11	Electric field increased
413-7-12	Corona discharge forms
413-7-13	Corona discharge--free electrons collide with gas molecules
413-7-14	Avalanche multiplication
413-7-15	Avalanche multiplication
413-7-16	Avalanche multiplication
413-7-17	Particle migration
413-7-18	Particle migration to collection electrode
413-7-19	Migration velocity
413-7-20	Particle removal--rapping
413-7-21	Particle removal--falling into hopper
413-7-22	Particle removal--removal from hopper
413-7-23	Probability of particle in the boundary capture layer
413-7-24	Collection efficiency formula
413-7-25	Power requirements
413-7-26	Power requirements--work on particle
413-7-27	Particle reached the terminal velocity
413-7-28	Work--power requirement
413-7-29	Particle migration velocity
413-7-30	Relationships between particle size, particle migration velocity, ESP power required
413-7-31	High collection efficiency
413-7-32	Economical to operate

413-7-33	Treat large volumes of gas
413-7-34	Flexible for various gas temperatures
413-7-35	Long useful life
413-7-36	Long useful life
413-7-37	Long useful life

CONTENT OUTLINE

Course: 413 - Lesson 7
Lecture Title: ESP - PRINCIPLES AND OPERATION

Page 1 *of* 11

NOTES

I. Lecture Introduction

Live shots
413-7-1

NOTE: make sure all structural component are described

The fundamental principles underlying the application of electrostatic forces to precipitate particles suspended in a gas were known in the 18th century. The successful development of a device that employed electrical gas cleaning methods did not take place until professor Fredrick Cottrell designed and built the first industrial ESP at the Detroit-Edison Trenton Channel Steam generator in 1923. Today there are more than 1300 ESP's in operation for the control of fly ash emissions from steam generators. The ESP is also an effective device for controlling emissions from cement kilns, pulp and paper plants, acid plants, sintering operations, etc. It is extensively used where dust emissions are less than 10-20 μm in size with a predominant portion in the submicron range.

The electrostatic precipitator is comprised of basically three essential components which we will discuss in detail later in the lecture.

413-7-2

They are:

1. Discharge electrode
2. Collection electrode
3. Rappers

NOTE: Point out components

1. Discharge electrode - wires that vary in shape, but are usually a small diameter wire (.1 in.) where the corona discharge occurs. We will discuss this in greater detail a little later.
2. Collection electrode - consist of either a tube of flat plate which is oppositely charged (relative to discharge electrode) and it is the surface where the charged particles are collected.
3. Rappers - are used to dislodge the dust at the collection electrode.

II. There are several types of ESP to consider. We will deal with the type used most by power plants.

413-7-3

1. Negative discharge single-stage ESP

413-7-4

   a. Discharge (corona) electrode has negative polarity.
   b. High-voltage is used to creat stronger electric field before reaching spark-over
   c. Particle charging and migration field created in one area simultaneously.

d. Not used for air conditioning applications because of high ozone formation

e. Two types - tube; plate

2. Two-stage ESP — 413-7-5

a. Generally used for air purification or air conditioning applications — 413-7-6

b. Separate charging and collecting areas

c. Positive polarity to cut ozone

d. Lower voltage drop

3. Wet-walled Precipitator -- cleaning is achieved by H_2O spray or agglomerated H_2O droplets. — 413-7-7, 413-7-8

III. The precipitator provides three essential functions

A. Charging suspended particles — 413-7-9

1. Particle charging accomplished by ions

2. Ions produced by high voltage direct current corona

B. Charged particles are subjected to an electric field which drives them to the collection electrode

1. Collection forces are applied directly to the particle; $\approx$ 3000 times force of gravity

2. Mechanical collectors treat the whole mass of gas

a. Precipitators much lower energy requirements

b. Extremely low draft losses

C. Particles at the collection electrode must be removed and carried away

1. Dry ESP - rapping (impact or vibration)

2. Wet ESP - water walled collection electrode

D. This gives basic overview of the ESP. We want to get into the fundamentals of these operations.

IV. Gas Ionization and Particle Charging

A. Accumulated charge -- most particles have some

1. Frictional electrification

2. Flame ionization

3. These are not large enough for economical operation of the ESP

B. Corona Discharge (Assume plate type ESP) — 413-7-10

1. Corona is produced by applying a high d-c electrical field between two electrodes

- a. High negative voltage is applied to the electrode with a small radius
- b. The other electrode is a large plate (relative to wire)
- c. The large electrode or plate is the collecting electrode

2. The electric field is increased until corona starting voltage is reached — 413-7-11
    - a. No current flows between electrodes until this point
    - b. Electrical breakdown of gas surrounding the discharge electrode begins
    - c. Blue glow around electrode -- ultraviolet radiation from positive ions striking the wire.
3. Increased voltage continues until spark-over voltage is reached — 413-7-12
    - a. Corona discharge -- is intense electrical breakdown of gas adjacent to small radius electrode
    - b. Spark over -- electrical breakdown of gas only in narrow paths of spark to collection electrode
4. The intense electric field close to the discharge electrode accelerates electrons — Slides are organizers. Use notes (add or subtract as necessary)
    - a. Electrons can be emitted from wire
    - b. Some ion-pairs exist in a gas at STP — 413-7-13
    - c. Sluggish positive ions move toward discharge electrode (produce electrons by secondary emissions - photoemission)
    - d. Free electrons are accelerated and collide with gas molecules (particles)
5. When the applied electric field reached a critical value the free electrons acquire enough energy between collisions to remove a gas molecule valence electron.
6. The free electrons continue to accelerate and ionize other neutral gas molecules — 413-7-14, 413-7-15
    - a. This is called Avalanche Multiplication — 413-7-16
    - b. The corona starting voltage can be calculated - but we will not cover that here
    - c. This voltage (power) requirement is uniquely determined by gas density.

- d. Pressure and temperature effect corona through their effect on gas density.
- e. To get lowest starting voltage you need smallest radius discharge electrode possible. Usually 0.05 - 0.15 in.

7.
- a. As the electrons leave the corona region and enter the inter-electrode region, where the magnitude of electric field is diminished, electron velocity decreases.
- b. When electrons impact on gas molecules in the inter-electrode region, they are captured, and negative gas ions are created.
- c. The stable concentration of negative ions migrating toward the grounded electrode produces a small space charge in the inter-electrode region.
- d. Increases in applied voltage will increase electric field strength and ion formation, until the avalanche formation of positive ions extends across the inter-electrode region and spark over occurs.

C. Field charging (particles > 2.0 microns) 0.5 μm too

1. Field charging of particles suspended in the gas stream is related to directed flow of ions in the interelectrode space.
2. Particulate in the interelectrode space
   - a. Dielectric constant greater than 1
   - b. Local electric field lines will be distorted toward the particle

   - c. Ions follow the electric field lines - maximum voltage gradient
   - d. Ions impact on the particles and are held by image charge forces
   - e. Particle gains charges - negative ions
3. This charge is negative because it is acquired in the area close to the discharge electrode where negative ions are moving toward the collection electrode

413-7-17

4. The charge on the particle is usually acquired in $\approx$ 0.01 seconds

$q_s = 4 \pi \varepsilon_o r^2 E_{cp}$

ε_o = permittivitity of free space 8.86×10^{-12} F/M

$3 \approx P - 2[(K-1)/K+2] + 1$

E_c = charging field V/m

K - particle dielectric constant

NOTE: This is for theoretical interest. No emphasis is necessary.

Maximum charge

$q_s = 12 \pi \varepsilon_o r^2 E_c$

5. As the particle is bombarded it gains enough charge to create a self-field until it reaches saturation charge

6. It will then move toward the collection electrode

413-7-18

D. Diffusion Charging (particles < 0.2 µm)
   1. Related to random motion of ions owing to their thermal velocity
   2. Average gas molecule velocity related to temperature
   3. Some molecules will have very high velocity and collide with the small particles

V. Particle Migration
   A. Migration Velocity
      1. Once a particle is charged the particle will migrate toward the collection electrode.
      2. An indicator of how the particle migrates is call the migration velocity ω.
      3. The migration velocity parameter represents the collectability of the particle within the confines of a specific collector.
   B. Migration velocity value
      1. The migration velocity is comprised of

413-7-19

$$w = \frac{d_p E_o E_p}{4 \pi \mu}$$

where d_p = the diameter of the particle, microns

E_o = strength of field in which particles are charged, stat-volts per cm. (represented by peak voltage)

E_p = strength of field in which particles are collected, stat-volts per cm. (normally the field close to the collecting plates)

μ = viscosity of gas, poises

C. Migration velocity is quite sensitive to the voltage since the electric field appears twice in the previous equation. Therefore one must design the precipitator using the maximum voltage fields with proper corona current flow for a maximum collection efficiency.

VI. Particle Removal From Collection Plates

- A. Forces acting on the particle at the collection plate
    - 1. Particles that are good conductors
        - a. Lose negative charge to collection electrode
        - b. Begin to gain positive charge and be repelled from the collection electrode
    - 2. Particles that are poor conductors
        - a. Lose negative charge slowly
        - b. Negative gas ion rain on dust layer keeps particle negative and attracted to electrode
    - 3. Short range intermolecular forces between adjacent particles and the electrode
        - a. Hold particles to the electrode
        - b. Cause deposited dust to form aggregates
    - 4. Gas velocity gradient tends to lift dust from the electrode
    - 5. Electric wind produced by gas ions can re-entrain dust
    - 6. Too frequent or intense rapping causes dust to fall as small aggregates
        - a. If done right large aggregates would fall into hopper
        - b. Smaller aggregates can be re-entrained
- B. Effects of accumulated dust layer on ESP efficiency
    - 1. If the dust accumulates to an excessive thickness gas velocity in the decreased passage will increase
    - 2. Dust on both electrodes reduces corona discharge current.

Increasing voltage to restore current can create back corona.

3. Dust layer acts as a resistor in series decreasing field strength
4. Dust layers can have high field strength. If high resistivity dust is present back corona results
5. Dust on the discharge electrode quenches the corona

C. Collection Electrode Cleaning Methods

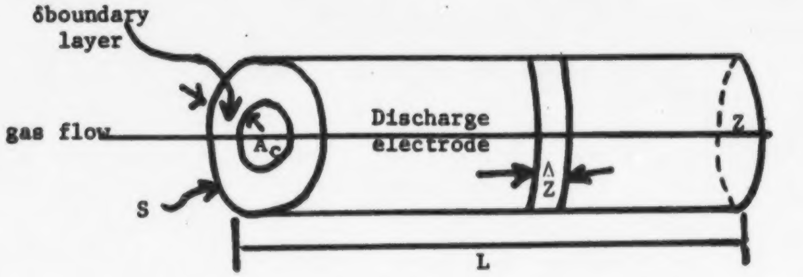
1. Several types — 413-7-20
    - a. Electrode rapping
    - b. Water film
2. Electrode rapping
    - a. This is the most common system
    - b. Electrodes are joined by a rapping bar
        - (1) Bar is struck by a weight or vibrated
        - (2) Dust falls from electrodes into hopper
    - c. It is important to rap the electrodes so that the dust layer falls off as large aggregates
        - (1) Otherwise dust can be re-entrained
        - (2) Rapping should be gentle and infrequent but thorough (50g); usually more frequent on the first section to handle higher particulate build-up.
    - d. Dust aggregates will be larger and are composed of fine particles
        - (1) Fine particles form aggregates better
        - (2) Large particles have greater tendency to re-entrain but are easier to recapture.
    - e. Optimum rapping cycle cannot be well predicted during ESP design
        - (1) Rapping cycle determined by empirical data
        - (2) While machine operates
        - (3) Rappers must be adjustable
        - (4) Typical times 5 min. rapping/60 min.
    - f. Common practice to sectionalize rapping
        - (1) Sections rapped independently
        - (2) Prevents puffing

g. Rapper types
(1) Impulse
(2) Hammer
(3) Vibrator - least desirable; can be self destructive when hard-to-remove dust is present
3. Water wall cleaning
a. Usually for tube type precipitators
b. H_2O distributed evenly over collecting surface
c. Resistivity and re-entrainment problems greatly reduced
D. Dust Hoppers 413-7-21
1. Dust dislocated from plates falls into hoppers
2. Hoppers should be frequently cleaned to prevent dust build-up 413-7-22
3. Baffles are effective in preventing gas sneakage
4. Hoppers should be insulated to prevent caking if dry ash removal is used
5. Hoppers should have steep side walls to prevent accumulation and plugging
VII. Collection Efficiency
1. The equation for collection efficiency holds the following assumptions
a. Particle charge time is negligible - we have seen it is small
b. Migration velocity is constant for all particles and large compared to bulk flow velocity near plate
c. Particle concentration is uniform in any ESP cross section
d. Uniform gas flow velocity except at boundary regions near collection plate
e. No disturbances (i.e. re-entrainment, back corona, etc.)
2. In the boundary layer near the collection electrode gas flow is laminar
a. Friction between gas and wall
b. Particle velocity toward wall is resultant of vector sum of gas velocity and electric force
c. $\delta = w(\Delta t)$ boundary layer thickness
3. The equation for efficiency is derived from the particle

migration velocity in the boundary layer and the distance it moves in the precipitator

a. This is simply the probability the particle is in the boundary capture layer

b. Diagram of concept



↗ wafer sections = $\frac{L}{Z}$

c. The gas will move through the ESP

$$\Delta Z = v(\Delta t)$$

d. The thickness of the layer then is

$$\delta = w(\Delta t) = w\frac{\Delta Z}{v}$$

e. The probability is then (S = perimeter of tube)

$$P = \frac{S\delta}{A_c} = \frac{Sw}{A_c}\frac{\Delta Z}{v} = \frac{SwL}{A_c vn}$$

$$= 1 - \frac{SwL}{A_c vn}$$

f. For the entire precipitator

$$P = (P_n)^n = \left[1 - \left(\frac{SwL}{A_c vn}\right)\right]^n$$

g. As n approaches ∞

$$\lim_{n\to\infty} (P_n)^n = \lim_{n\to\infty} \left(1 - \frac{SwL}{A_c vn}\right)^n = e^{-\frac{SL}{A_c v}w}$$

h. $A_c V = Q$ and SL = collection area so

$$\eta = 1 - e^{-(A/Q)w}$$

Slide of Derivatio
for added student
interest (optional
Use board for rest
of Derivation.
This derivation
may not be necessa

413-7-23

4. Deutsch-Anderson Equation

   a. This equation describes the factors involved in the collection efficiency of the precipitator:

$$\eta = 1 - e^{-\left(\frac{A}{Q}\right)w}$$

   where η = collection efficiency
   A = effective collecting electrode
   Q = gas flow rate through the precipitator
   w = migration velocity

   b. This shows that precipitator size is
      1. Inversely proportional to particle migration velocity
      2. Directly proportional to gas-handling capacity but independent of gas velocity (this is not true because velocity effects re-entrainment)

   c. While this equation is scientifically valid, there are a number of instances that can cause the exponent to be in error as much as a factor of two or more. Care must be taken when using this equation.

5. There are more sophisticated methods for calculating efficiency but this is good for estimation. Effects not included:
   a. Concentration distribution
   b. Particle size distribution
      (1) All considered one size
      (2) Uniform size throughout machine
   c. Variation in electrostatic force
   d. Reynold Number effect on particle drag
   e. Slip correction factor
   f. Gas velocity variation

413-7-24

Slide of efficiency equation must be shown, do it at end of series.

VIII. Power Requirements

1. Theoretical power can be calculated by
   a. Work = Force x Distance
      The work to move the particle by electrostatic force to the collection electrode
   b. Work = $F_E(s)$ s = distance

413-7-25

413-7-26

c. The particle is at terminal velocity so
$F_E = F_D$ and $F_D = 6\ \pi\mu rw$

d. Therefore: work = $6\ \pi\mu rw(s)$/per particle 413-7-27

e. This may be rearranged to show 413-7-28
Power = VI = $6\ \pi\mu r(w)(s)$

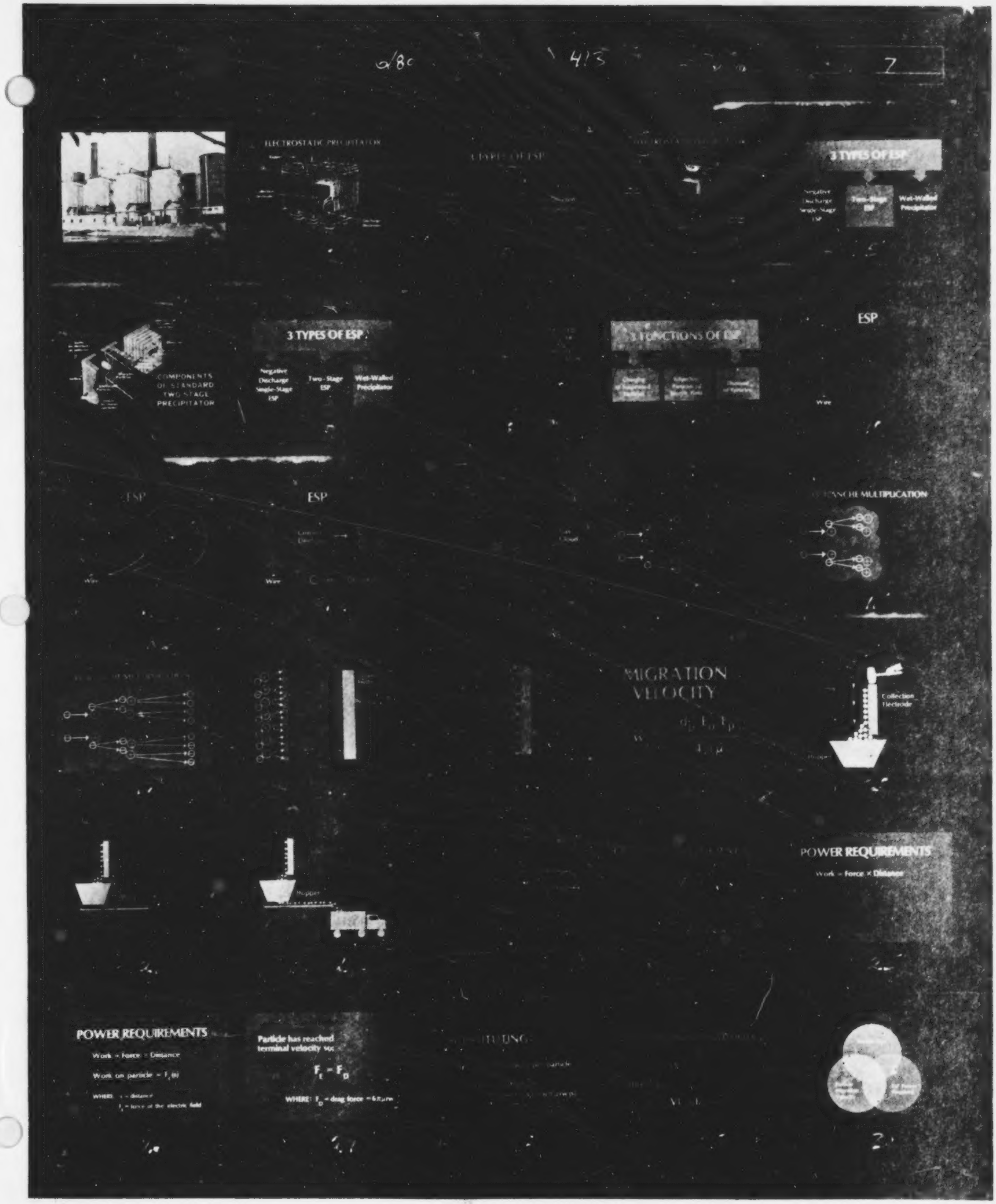
f. The key then is the particle migration velocity 413-7-29
$w = \frac{qEp}{6\ \pi\mu r} \quad \therefore\ VI = qE_p(s)$

g. These items illustrate the relationships between 413-7-30
(1) particle size
(2) particle migration velocity
(3) ESP power requirements

IX. The features of the ESP which make it particularly attractive are:

1. They can be designed for high collection efficiency for particles of all sizes 413-7-31
2. They are economical to operate since they have relatively low internal power requirements and 413-7-32
inherently low draft losses (pressure drop) 413-7-33
3. They can treat large gas volumes 413-7-34
4. They are very flexible in gas operating 413-7-35
temperature used -- 200°F - 800°F 413-7-36
5. They have a long useful life 413-7-37

280 413 7



ELECTROSTATIC PRECIPITATOR

3 TYPES OF ESP

3 TYPES OF ESP

Negative Discharge Single-Stage ESP

Two-Stage ESP

Wet-Walled Precipitator

COMPONENTS OF STANDARD TWO-STAGE PRECIPITATOR

3 TYPES OF ESP

Negative Discharge Single-Stage ESP

Two-Stage ESP

Wet-Walled Precipitator

3 FUNCTIONS OF ESP

ESP

ESP

ESP

AVALANCHE MULTIPLICATION

MIGRATION VELOCITY

$$w = \frac{d_p E_o E_p}{4 \pi \mu}$$

POWER REQUIREMENTS

Work = Force × Distance

POWER REQUIREMENTS

Work = Force × Distance

Work on particle = $F_E(x)$

WHERE: x = distance

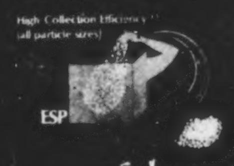
F_E = force of the electric field

Particle has reached terminal velocity so:

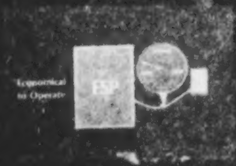
$$F_E = F_D$$

WHERE: F_D = drag force = $6 \pi \mu r w$

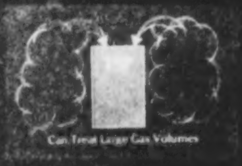
6/80 413 L-7 NO.


High Collection Efficiency (all particle sizes)
ESP

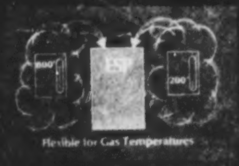
31


Economical to Operate
ESP

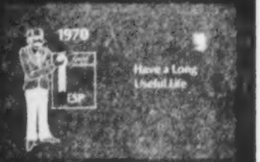
32


Can Treat Large Gas Volumes

33


800°
ESP
200°
Flexible for Gas Temperatures

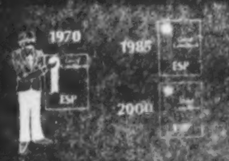
34


1970
ESP
Have a Long Useful Life

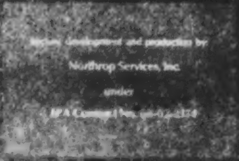
35

1970
1985
ESP

36


1970
ESP
1985
ESP
2000
ESP

37



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EPA Contract No. [illegible]

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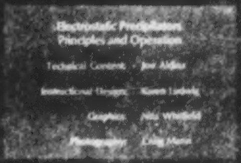

Electrostatic Precipitators
Principles and Operation

Technical Content: [illegible]

Instructional Design: Karen Ludwig

Graphics: Nita Whitfield

Photography: [illegible]

39

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LESSON PLAN

AIR POLLUTION TRAINING INSTITUTE

TOPIC: ESP: DESIGN AND APPLICATIONS

COURSE: 413 - Lesson 8
LESSON TIME: 1 hour
PREPARED BY: G. J. Aldina DATE:
Revised by David S. Beachler 12/1/79

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

LESSON GOAL: This lesson is an extension of the ESP Theory lecture. It will point out problems affecting the ESP, controls for the machine, and uses of the unit.

LESSON OBJECTIVES: The student should be able to:

- * Describe factors affecting the operation of an electrostatic precipitator.
    - Particle resistivity
    - Gas stream parameters
    - Gas flow distribution
- * Discuss common operating problems of ESP's.
- * Describe controls used for the ESP.
- * List recommended maintenance and operating procedures for assuring optimum ESP performance.

REFERENCES: Theodore, L. and Buonicore, A. J., Industrial Air Pollution Control Equipment for Particulates, CDC Press, Cleveland, Ohio, 1976, pp. 174 - 178

AUDIO-VISUAL MATERIALS FOR LESSON 8

Lesson 8 Electrostatic Precipitator Design and Applications

413-8-1	Electrostatic precipitator
413-8-2	Resistivity - definition
413-8-3	Normal resistivity
413-8-4	Low resistivity
413-8-5	High resistivity
413-8-6	Conditioning high resistivity
413-8-7	Effects of temperature and moisture on resistivity
413-8-8	Low sulfur coal - generally has high resistivity
413-8-9	Typical flow distribution
413-8-10	Live shot of flow distributors
413-8-11	Stage or field construction
413-8-12	Parallel sections
413-8-13	ESP - shell
413-8-14	Live shot - ESP shell
413-8-15	Electrodes
413-8-16	Typical collection plates
413-8-17	Discharge electrodes
413-8-18	Live shot - discharge wires and collection plates
413-8-19	Rappers
413-8-20	Live shot - rappers
413-8-21	Live shot - rappers
413-8-22	High voltage equipment
413-8-23	Live shot - high voltage equipment
413-8-24	Live shot - ESP metering equipment
413-8-25	Broken wires
413-8-26	Primary emters
413-8-27	Secondary meters
413-8-28	Live shot of insulator
413-8-29	Live shot of rapper and protective bad weather caps
413-8-30	Live shot of protective bad weather caps; not in proper position
413-8-31	Hoppers
413-8-32	Review

CONTENT OUTLINE

Course: 413 - Lesson 8
Lecture Title: ESP: DESIGN AND APPLICATIONS

Page 1 *of* 11

NOTES

The preceeding lecture has covered the basic theory of electrostatic precipitation of particles suspended in a gas stream. This lecture is directed at pointing out various particle and gas stream characteristics that effect the operation of the ESP. Knowledge of ESP theory will make this discussion of operating problems easier and more meaningful.

413-8-1

(413-7-2)

Note: Review of the previous lecture would be helpful - discussion of discharge wires, electrodes, rappers, etc.

I. Particle Resistivity

  A. Definitions

    1. Resistance - property of a circuit or substance opposing the flow of current and causing heat when current flows. Unit is Ohm. 1 amp flowing through 1 ohm resistance causes 1 watt (10^7 erg/sec) of heat.

413-8-2

    2. Particle resistivity is the term used to describe the ability of particles to take on a charge.

    3. Measuring resistivity of a dust sample

      a. Apparatus is a plate with a needle discharge electrode suspended above it

Note: This topic can be touched upon lightly.

      b. Collected dust is suspended in a gas stream then passed thru the plate and needle apparatus

      c. The needle produces a strong corona, precipitating the dust

      d. When $\approx$ 1 mm dust thickness is collected the collection plate is grounded through a resistance varied between 10^5 - 10^{11} ohms

      e. A movable disk concentric to the discharge needle is lowered onto the dust layer

      f. Dust layer thickness is precisely measured

      g. Upper disk is charged at 100V

      h. Current flow is measured through the dust and series resistance

      i. Current flow measurement is repeated at progressively higher voltages → $\approx$ 20 KV/cm

      j. Resistivity is calculated from the equation

  B. Particle resistivity can vary between 10^{-3} to 10^{14} ohm-cm

413-8-3

1. Dust below 10^4 ohm-cm is difficult to retain on collecting electrode - Low Resistivity 413-8-4
    a. This dust is readily charged and migrates to the collection electrode
    b. Rapidly loses negative charge then acquires heavy positive charge
    c. Particle can spring back into gas stream if positive charge gets high enough
2. Dust above 10^{11} ohm-cm - High Resitivity 413-8-5
    a. Collected dust is subjected to a rain of negative ions and particles
    b. Accumulated charge must be dissipated by current flow through the dust layer
    c. Voltage drop = $\frac{\rho_B \times D^{I}}{A} \approx 20$ KV

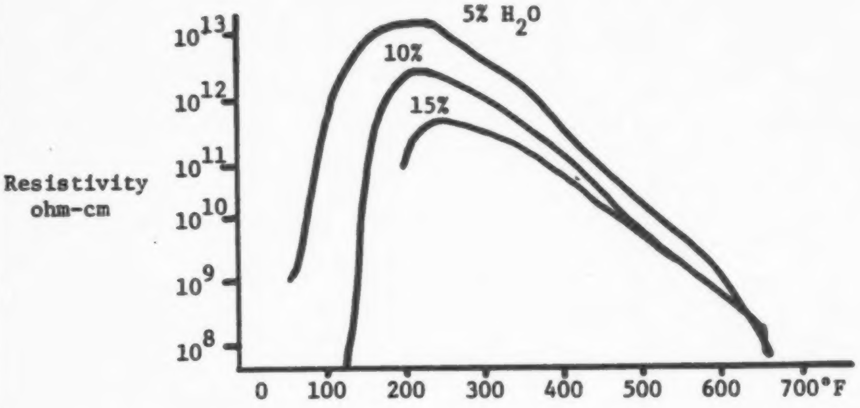
       $I = 2 \times 10^{-8}$ a/cm^2
       $\rho_B = 10^{12}$ ohm-cm
       X_D - 1 cm
    d. This is the area in which electrical breakdown of the dust occurs
    e. Observed as glowing spots on plate. Sharp points at which intense spark-over takes place
    f. Break down produces electron-positive ion pairs
    g. Positive ions toward corona; negative electrons toward plate
    h. Results
        (1) Decreases charge on particles migrating toward collection electrode
        (2) Particle re-entrainment (of collected dust)
        (3) Total current increase; voltage decreases and so does field strength

C. Conditioning - to lower resistivity 413-8-6
1. Resistivity problems can be reduced by
    a. Lowering current density - not enough charge to particles so this is poor choice
    b. Lowering resistivity
2. Lowering resistivity is accomplished
    a. Spraying dust with H_2O or steam
        (1) Adheres to dust surfaces
        (2) Electrolytic film allows surface conduction

  - b. Dust that do not absorb H_2O can be conditioned
    - (1) SO_3 for basic dusts } as little as 20 ppm works
    - (2) NH_3 for acidic dusts }
- 3. Prevent air in leakage - lowers temp and humidity
- 4. H_2O effects electrical discharge
  - a. Each % H_2O increases spark voltage 5%
  - b. Reduces corona current 7% for each % H_2O
- 5. Particles that readily conduct charge could be added to the gas stream but this is usually not practical

D. Temperature Effects on Resistivity

413-8-7



1. Temperature increases but H_2O is evaporated
2. At maximum surface conduction is important compared to volume conduction.

II. Gas Stream Parameters

A. Temperature

1. Gas temperature affects particle resistivity
2. Gas temperature decrease generally lowers ash (particle) resistivity
3. Some problems could arise, however
   - a. plume bouyancy resulting from decrease
   - b. possible corrosion

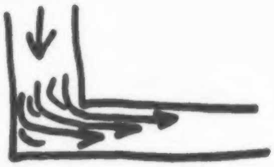
B. SO_3 Content of the Gas

413-8-8

1. In general, low sulfur coal will have high resistivity.

2. The controlled addition of sulfur trioxide (SO_3) has been reported to improve the performance of ESP's used for collection of fly ash from western coals (less than 1 percent sulfur content).
3. Careful control of the sulfur trioxide addition rate is required to avoid releasing of the gas.

III. Gas Flow Distribution
   A. An ESP is essentially a large box
      1. Gas flows through it 413-8-9
      2. The gas should flow slowly and evenly
   B. Low pressure drop ducts
      1. Keep total length to a minimum
      2. As few bends as possible
      3. Bends should have straightening vanes



   C. Gas Distribution in the ESP (gas velocity 2-8 ft/sec)
      1. For the exponential efficiency equation for the ESP it can be shown that the gas must be equally distributed to passages for max. efficiency.
      2. Good distribution of entering gas is tough to obtain
      3. Ideally gas distribution would be
         a. Plug - flow -- perfectly flat velocity profile 413-8-10
         b. Factors preventing this
            (1) process distortions of the flow
            (2) duct effects - bends, friction
            (3) duct velocity much higher than ESP so need expansion section
            (4) expansion section will need diffuser-perforated plate

CONTENT OUTLINE

Course: 413 - Lesson 8
Lecture Title: ESP: DESIGN AND APPLICATIONS

Page 5 *of* 11

NOTES

IV. Electrical Sectionalization

- A. Maximum field voltage depends on
  - 1. Gas and particle properties — 413-8-11
  - 2. These can vary from point to point within the ESP
  - 3. To maintain ESP at optimum efficiency the unit should be divided into stages
  - 4. Each section has separate power supply and controls
- B. Controls
  - 1. Higher voltage produces high spark rate between electrodes
  - 2. Optimum spark rate/section 50-150/min.
    - a. Corona power at best possible setting
    - b. Gains in particle charging are just offset by corona current losses from spark-over
  - 3. Above this spark rate
    - a. Input power is wasted in sparking
    - b. Less power applied to the dust
  - 4. The spark rate is maintained at optimum setting by momentarily lowering corona power when excessive sparking occurs
- C. Need for Stage or Fields (in series)
  - 1. Power needs differ at different ESP locations — 413-8-11 (keep up same slide)
  - 2. Inlet field or stage dust concentration is heavy
    - a. Heavy dust suppresses corona current
    - b. Requires great deal of power here to generate adequate corona discharge
  - 3. Downstream dust concentration is lower
    - a. Corona current flows more freely
    - b. If same power applied for it as at inlet excessive sparking will limit particle charging
    - c. One power supply would probably limit spark rate in downstream stages reducing inlet section efficiency
    - d. Individual controls and power supplies work much better
    - e. Also if a given state or field is out other fields are not as severely effected
- D. Parallel sectionalization - chamber — 413-8-12
  - 1. Copes with different power needs at inlet to ESP created by
    - a. Poor gas distribution

b. Uneven dust distribution

2. Adds only small increase in efficiency

3. Allows on-line maintenance of shorted sections

V. ESP Construction - Typical Design Parameters

A.

Typical Design Parameters for Electrostatic Precipitators

Parameter	Range of values
Precipitation rate (effective migration velocity)	0.1 - 0.7 ft/sec
Plate spacing	8 - 11 in.
Gas velocity	2 - 8 ft/sec
Plate height	12 - 45 ft
Plate length	0.5 - 2.0 times height
Applied voltage	30 - 75 kV
Corona strength	0.01 - 1.0 mA/ft of wire
Field strength	7 - 15 kV/in.
Residence (treatment) time	2 - 10 sec
Draft loss (pressure drop)	0.1 - 0.5 in. water
Efficiencies	to 99.9+%
Gas temperature	to 700°F (standard) 1,000°F (high temperature) 1,300°F (special)

Power = $1/2(V_p + V_m)I_c$

I_c = corone current

V_p = Peak voltage

V_m = Minimum voltage

(This calculation is for theoretical interest.)

simplified electric field = $\frac{i}{2 \pi K_o K}$

i = current/lenght

K = ion mobility

K_o = dielectric constant of a vacuum

B. Shell structure

413-8-13

1. Encloses the electrodes and supports them in a rigid frame

413-8-14

2. Structure and foundation should be conservatively designed

a. Especially critical for hot ESP's

b. Must be able to withstand thermal and structural stress

c. Plant in Wilmington, NC is rebuilding one that took this for granted

3. Convectional practice supports plates from top
4. Shell must be thoroughly insulated including hopper
    a. Conserve heat
    b. Prevent condensation - and subsequent possible corrosion
5. Easy access to the machine internals for repair and inspection
6. Connecting ducts must be insulated — 413-8-15

C. Electrodes
1. Ducts range between 8-12 inches wide
    a. 20-30 ft high use $\approx$ 9 in. spacing
    b. 35-45 ft high use $\approx$ 10-12 in. spacing
2. Aspect ratio - ratio of plate length to height
    a. Particle rapped from plate may take several seconds to fall into hopper
    b. Do not want it to be carried out of precipitation area before it can fall into the hopper
    c. Design aspect ratio for 99% + efficiency between 1 and 1.5
3. Collection electrodes - collection plates — 413-8-16
    a. Solid sheet metal plates
    b. Some have baffles to improve gas flow
    c. Must be rigid enough to maintain electrode spacing tolerances ± 5%
    d. Distorted or misaligned electrodes cause reduced operating voltage and efficiency
4. Discharge electrodes (many types of design)
    a. Traditionally round wire (0.1 in diameter) — 413-8-17
    b. The size (usually .1 - .15 in diameter) and shape of the discharge wires are governed by the corona and mechanical requirements of the system. Discharge wires can have many configurations, twisted, barbed, ribbon and other types are commonly used. — 413-8-18

       Note: This live shot shows both discharge and collection electrodes.
    c. Wires are held taught at the bottom by weight as to maintain consistent critical distance between wires and plates. (4 - 11 in spacing)
    d. Should have shroud on bottom and top part of wire to protect it

D. Rappers — 413-8-19
  1. Rapping can be done electromagnetically, pneumatically or mechanically.
  2. Rapping causes the dust to slough away from the electrode surfaces and fall into the collection hoppers. Rapping is done while the unit is on-line. — 413-8-20
  3. Rappers can be spaced every 5 feet along the plates. — 413-8-21
  4. Rapping must be done to the collection plates but also to the discharge wires (gently rapping) to prevent dust build up on the wires.
  5. Dust will sometime accumulate on the discharge wires. Occasionally the dust must be removed, usually by gentle vibration of the electrodes.

E. High Voltage Equipment
  1. Must be able to provide intense electrical fields and corona currents — 413-8-22, 413-8-23
    a. Must be reliable and stable
    b. Proper wave form (voltage waveform)
    c. Today this means silicon rectifiers
  2. Metering should include — 413-8-24
    a. Primary meters for
      (1) Total ESP volts
      (2) Total ESP milliamperes
    b. Secondary meters for each bus section
      (1) Voltmeter
      (2) Milliammeter
      (3) Spark rate meter

VI. Trouble shooting ESP operation - operation and maintenance
  A. Discharge wire breakage — 413-8-25
    1. Causes
      a. Kinks or knicks in wire
      b. Spit arcs at ends (prevented by shrouds)
      c. Fatigue - swinging
      d. Localized arcing
      e. Corrosion
    2. Indications of broken wires
      a. Full load current with reduced primary voltage

b. Rhythmic and repetitive arcing bursts

B. Ash resistivity problems are indicated

1. Sparking at low current densities

2. Low voltage, high current, steep corona characteristic could mean back corona formation

C. Reading high voltage instrumentation

1. Primary Voltmeter

a. No voltage -- open primary circuit — 413-8-26

b. High voltage -- faulty rectifier; open transformer; poor connection to ESP; open bus section

c. Low voltage -- insulator leak; high dust level in hoppers; poorly cleaned electrodes; swinging wires

2. Primary Ammeter

a. No current, high voltage -- open primary circuit

b. Very low current, high voltage -- open transformer primary

c. Irregular current, low voltage -- short

d. Broken wire shows low voltage, cycling current

3. Secondary Voltmeter -- Located between rectifier and discharge wire — 413-8-27

a. No voltage -- could be open primary circuit

b. High voltage -- open precipitator bus section; faulty rectifier

c. Low voltage -- same as Primary

4. Secondary Ammeter

a. No current, no voltage -- open circuit primary

b. Low current, high voltage -- open transformer primary or open secondary circuit

c. Irregular current, low secondary voltage -- excessive dust arcing etc. Broken wire in the swinging field shows cycling current

5. Spark meter -- above 100/min shows excessive power loss

D. Insulator Problems

1. Cracked or dust covered insulators cause problems with proper electrical operation — 413-8-28

2. Can be prevented by careful operation of ESP

a. Keep insulators above dew point of gas
b. Do not subject them to intense rapping
c. Pressurize compartment with warm air
d. Inspect regularly

E. Protective Covers — 413-8-29

1. Rubber covers protect the rappers from adverse weather conditions. (see slide) — 413-8-30
2. Covers should be tightened in correct position to avoid water leakage and shorting-out problems.

F. Hoppers — 413-8-31

1. Adequate hopper capacity must be provided to receive the dust after rapping and to contain it far enough below the baffles to preclude reentrainment.
2. Screw conveyors are normally used for emptying; adjustments might be necessary for design for sticky dusts.
3. Access doors and striker plates are useful for maintenance needs.

VII. Applications

A. Use of electrostatic precipitators have been applied to many industries over the year.

1. Can achieve 99.9+% collection efficiency
2. Can handle exhaust gas up to 1100°F.
3. Very efficient for even submicron data.

B. Selected Various Processes

a. Use in coal fired utilities and industrial boilers. Size range according to selected industrial application.
b. Usual efficiency 98 - 99.9+
c. Gas temperature 275 - 600 (usually 300 - 350)

2. Steel Industry
    a. Blast furnace gas
    b. Coke oven gas (tars)
    c. Basic oxygen furnaces
    d. Sinter plants
    e. Collect submicron particles for above industries
    f. Usual efficiencies vary from 95 - 99+%

3. Cement
   a. Used frequently on cement kilns, both wet and dry processes.
   b. Can collect sub micron particles up to 99+ efficiency
   c. Also used for dryers
4. Pulp and Paper Industry
   a. Used on black liquor recovery furnace
   b. 99% efficiency for sub micron particles

VII. Review

413-8-32

The past hour we've talked about the following subjects.

- Resistivity
- Flow distribution
- Sectionalization
  - Parallel
  - Fields or Stages
- Design Features
  - Shell
  - Collection Electrodes
  - Discharge Electrodes
  - Rappers
  - High Voltage Equipment

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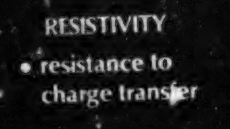
1



RESISTIVITY
- resistance to charge transfer

2

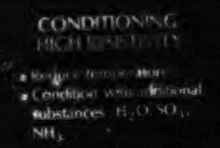
NORMAL RESISTIVITY

3

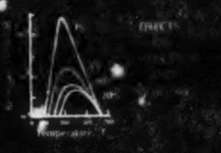
LOW RESISTIVITY

4

HIGH RESISTIVITY



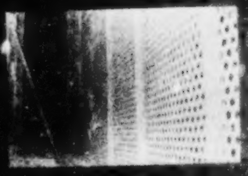
CONDITIONING HIGH RESISTIVITY
- Reduce temperature
- Condition with additional substances H_2O, SO_3, NH_3



7

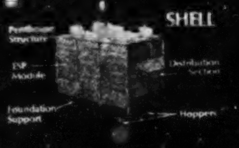
Low
Sulfur
Coal

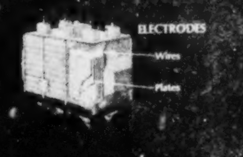
TYPICAL FLOW DISTRIBUTION



Stage 1
Stage 2
Stage 3

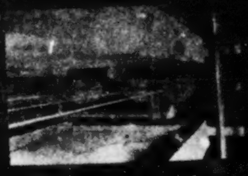
PARALLEL SECTIONS

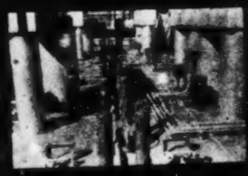

SHELL
Penthouse Structure
ESP Module
Distribution Section
Foundation Support
Hoppers


ELECTRODES
Wires
Plates

TYPICAL COLLECTION PLATES

DISCHARGE ELECTRODES





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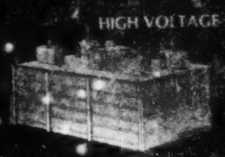
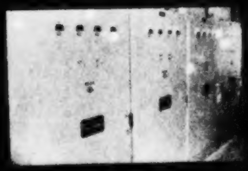
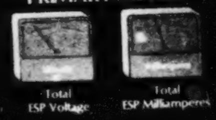

HIGH VOLTAGE

22

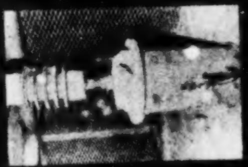


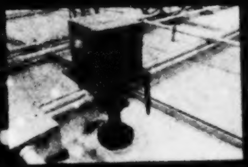
BROKEN WIRES


PRIMARY METERS
Total ESP Voltage
Total ESP Milliamperes

SECONDARY METERS
Voltmeter
Milliammeter
Sparkmeter

27





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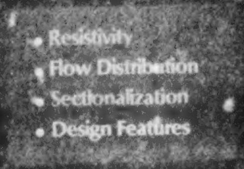
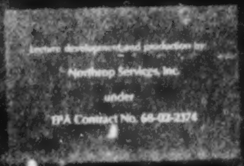


- Resistivity
- Flow Distribution
- Sectionalization
- Design Features

32



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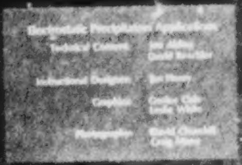

Electrostatic Precipitation Applications

Technical Content	[illegible] David Beachler
Instructional Designer	[illegible]
Graphics	[illegible] Linda White
Photographer	[illegible]

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LESSON PLAN

AIR POLLUTION TRAINING INSTITUTE

TOPIC: PROBLEM SESSION V - ELECTROSTATIC PRECIPITATOR

COURSE: 413 - Lesson 8a
LESSON TIME: 1 hour
PREPARED BY: G.J. Aldina
DATE: 7/79

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

LESSON GOAL:	Briefly describe the use of electrostatic precipitator formulas such as migration velocity and collection efficiency by solving four problems.
SUPPORT MATERIAL AND EQUIPMENT	1. Chalkboard 2. 413 Student Workbook pp 17-20.

CONTENT OUTLINE

Course: 413 - Lesson 8a
Lecture Title: PROBLEM SESSION V - ELECTROSTATIC PRECIPITATOR

NOTES

I. Problem 5-1

A. Work our problem 5-1 for the students. The solution is:

NOTE: See problem 5-1 on page 17 in the 413 Student Workbook

5.1 ESP Problem

An electrostatic precipitator consists of two parallel 10 ft high by 16 ft wide plates with corona wires positioned half way between the plates. Find the effective migration velocity at a flow rate of 35 acfs if the required collection efficiency is 0.95.

SOLUTION:

ESP has 2 plates 10 ft high and 16 ft wide. What is migration velocity if flow rate is 35 acfs and efficiency is 0.95.?

$$\eta = 1 - e^{-(A/Q)w}$$

$$-w \frac{A}{Q} = \ln (1 - \eta)$$

$$w = \frac{Q}{A} (1 - \eta) = - \frac{35 ft/sec}{(10 ft)(16 ft)(2)} \ln (1 - 0.95)$$

$$w = 0.328 \text{ ft/sec}$$

II. Problem 5-2

A. Work out problem 5-2 for the students. The solution for Problem 5-2 is:

NOTE: See problem 5-2 on page 18 of the 413 Student Workbook

5.2 ESP Problem*

A horizontal-flow-single-stage electrostatic precipitator is used to remove particulates from a dry process gas stream of a Portland cement manufacturing plant. The precipitator consists of multiple ducts formed by collecting plates 14 ft wide by 16 ft high and placed 9 inches apart. The rate of flow through each duct is estimated to be 2400 acfm and the content of dust is 5 grains/ft^3.

- **a. Calculate the collection efficiency.**
- **b. Calculate the amount of dust collected by a duct each day.**

***Assume w = 0.19 ft/sec**

SOLUTION:

(a) $\eta = 1 - e^{-(A/Q)w}$

$A = 2(14)(16) = 448 \text{ ft}^2$

$Q = \dfrac{2400 \text{ACFM}}{60 \text{ sec/in}} = 40 \text{ ft}^3\text{/sec}$

$\eta = 1 - e^{-(0.19)\left[448/40\right]} = 0.881$

(b) $\#/\text{day} = \dfrac{0.88(5 \text{ gr/ft}^3) \times (2400 \text{ ft}^3\text{/min}) \times (60 \text{ min/hr})\ 24 \text{ hr/day}}{7000 \text{ gr/\#}}$

$= 2175\ \#/\text{day}$

III. Problem 5-3

A. Allow students 20 minutes to work on problem 5-3

B. Go over the solution of problem 5-3. The solution is:

NOTE:
See problem 5-3 on page 19 of the 413 Student Workbook

5.3 ESP Problem

An electrostatic precipitator has three ducts with plates 12 ft wide and 12 ft high. The plates are 8 inches apart.

a. Assuming a uniform distribution of particles and a drift velocity of 0.4 ft/sec, calculate the collection efficiency at a rate of flow of 4,000 acfm at 20°C and 1 atm.

b. Calculate the efficiency if one duct were fed 50% of the gas and the others 25% each.

SOLUTION:

(a) $A = 2(12)^2 = 288 \text{ ft}^2/\text{duct}$

$Q = \frac{4000}{60} \times \frac{1}{3} = 22.2 \text{ ft}^3/\text{sec for each duct}$

$\eta = 1 - e^{-(0.4)(288/22.2)} = 1 - (5.6 \times 10^{-3}) = .9944$

(b) $A = 288\text{ft}^2/\text{duct}$

$Q = \frac{4000}{60} \times \frac{1}{2} = 33.33 \text{ ft}^3/\text{sec}$

$\eta = 1 - e^{-(.4)(288/33.33)} = 1 - (3.1 \times 10^{-2}) = .9684$

25% Duct

$A = 288 \text{ ft}^2/\text{duct}$

$Q = \frac{4000}{60} \times \frac{1}{4} = 16.7 \text{ ft}^3/\text{sec}$

$\eta = 1 - e^{-(.4)(288/16.7)} = 1 - (1.01 \times 10^{-3}) = .9989$

Overall Efficiency

$\eta = 0.5\ (.9684) + 2(.25 \times .9989) \times 100 = 98.37\%$

IV. Problem 5-4

A. Have students do problem 5-4 for homework.

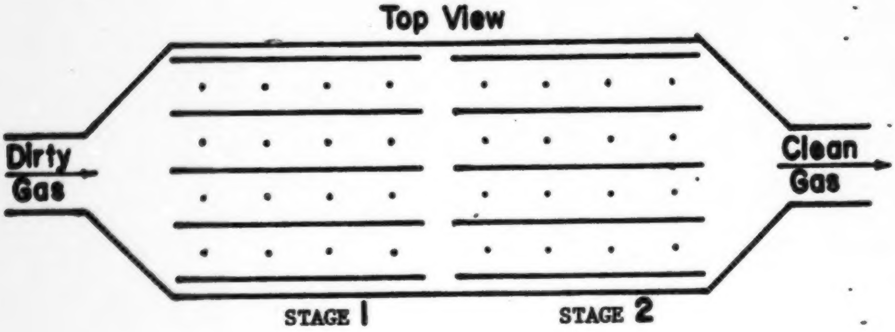
B. Go over the solution for Problem 5-4. The solution is:

NOTE: See problem 5-4 on page 20 of the 413 Student Workbook

5.4 A precipitator consists of two stages, each with five plates in a series (see figure below). The corona wires between any two plates are independently controlled so that the remainder of the unit can be operated in the event of a wire failure.

The following operating conditions exist:

Gas Flow Rate	**10,000 acfm**
Plate Dimensions	**10 ft x 15 ft**
Drift Velocity	**19.0 ft/min Section 1**
	16.3 ft/min Section 2



a. Determine the normal operating efficiency.

b. During operation, a wire breaks in Stage 1. As a result, all of the wires in that row are shorted and ineffective, but the others function normally. Calculate the collection efficiency under these conditions.

c. Similarly, a wire breaks in Stage 2 after Stage 1 is repaired. What is the overall collection efficiency of the unit under these conditions?

5.4

SOLUTION:

(a) $A = 10 \times 15 \times 8 = 1200 \text{ ft}^2$

$Q = 10{,}000$ ACFM

$\eta_1 = 1 - e^{-(1200/10{,}000)(19)} = 0.89772$

$\eta_2 = 1 - e^{-(1200/10{,}000)(16.3)} = 0.85858$

$$\eta_{Total} = 1 - (1-\eta_1)(1-\eta_2)$$

$$= 1 - (1-0.89772)(1 - 0.85858) = 0.98554$$

(b) $$\eta_{Total} = 1 - \left[1-(0.75)\ \eta_1\right]\left[1-\eta_2\right]$$

$$= 1 - \left[1-(0.75)(.89772)\right]\left[1 - 0.85858\right] = 0.95380$$

(c) $$\eta_{Total} = 1 - \left[1 - 0.89772\right]\left[1-(0.75)(0.85858)\right] = .96358$$

LESSON PLAN

AIR POLLUTION TRAINING INSTITUTE

TOPIC: FABRIC FILTER PRINCIPLES

COURSE: 413 - Lesson 9
LESSON TIME: 1 1/2 hours
PREPARED BY: David S. Beachler
DATE: 4/79

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

LESSON GOAL:

Briefly describe the principles involved in the collection of particulates by fabric filtration and describe the main aspects of a baghouse such as filtering, cleaning of the bags, filter materials, pressure drop and collection efficiency.

LECTURE OBJECTIVE:

At the end of the lesson the student should be able to:

* List three collection mechanisms used in fabric filtration.
* Briefly describe the three general designs for baghouses.
* List four cleaning mechanisms and briefly describe their operation.
* Name two types of fabric filter material construction and the use of different fiber types to guard against failure of fabric materials.
* Define pressure drop and recall the simplified formulas for determination of Δp across the cake and across the fabric.
* Describe the sieving action and the formation of the cake, and the role played in terms of collection efficiency.
* Define filtration velocity and air to cloth ratio and the role they play in terms of fabric filtration performance.

STUDENT PREREQUISITE SKILLS:

Ability to understand basic principles of physical science and perform calculations with logarithms and exponential functions

LEVEL OF INSTRUCTION: Advanced

INTENDED STUDENT PROFESSIONAL BACKGROUND: Engineering or Physical Science

SUPPORT MATERIALS AND EQUIPMENT:

1. slide projector
2. overhead projector
3. chalkboard
4. 413 Student Manual

REFERENCES:

1. 413 Student Manual
2. "Air Pollution Control Technology, An Engineering Analysis Point of View", by Robert M. Bethea, Van Nostrand Reinhold Company, New York, 1978.
3. "Particulates and Fine Dust Removal", by Marshall Sittig, Noyes Data Corporation, Park Ridge, New Jersey, 1977.
4. "Procedures Manual for Fabric Filter Evaluation," EPA 600/7-78-113, IERL Research Triangle Park, N. C., June 1978.
5. "Proceedings The User and Fabric Filtration Equipment Specialty Conference", the Niagara Frontier Section, Air Pollution Control Association, Pittsburgh, PA, October 1973.
6. "Proceedings The User and Fabric Filtration II Equipment Speciality Conference", the Niagara Frontier Section, Air Pollution Control Association, Pittsburgh, PA, October 1975.
7. "Proceedings The User and Fabric Filtration III Equipment Speciality Conference", The Niagara Frontier Section, Air Pollution Control Association, Pittsburg, PA, October 1978.
8. "Industrial Air Pollution Control Equipment for Particulates", by L. Theodore and A. J. Bounicore, CRC Press, Inc., Cleveland, OH, 1976.

9. "Handbook of Fabric Filter Technology. Vol. I. Fabric Filter Systems Study", Charles E. Billings, et. al., distributed by NTIS, PA-200-648, December, 1970.

10. "Appendices to Handbook of Fabric Filter Technology, Vol. II. Fabric Filter Systems Study", GCA Corporation, Bedford, Massachusetts, distributed by NTIS. PA-200-649, December 1970.

11. "Fabric Filter Cleaning Studies", EPA Technology Series, EPA 650/2-75-009, January 1975.

AUDIO-VISUAL MATERIALS FOR LESSON 9

Lesson 9 Fabric Filter Principles

413-9-1	Baghouse--live shot
413-9-2	Baghouse--live shot
413-9-3	Collection mechanisms
413-9-4	Impaction
413-9-5	Interception
413-9-6	Diffusion
413-9-7	Gravitation
413-9-8	Electrostatic attraction
413-9-9	Filter designs
413-9-10	Interior filtration
413-9-11	Exterior filtration
413-9-12	Bags--hanging in baghouse
413-9-13	Support cages for bags
413-9-14	Single units--interior shot of a pulse jet baghouse
413-9-15	Compartmental baghouse units
413-9-16	Hoppers and cleanout pipes
413-9-17	Cleaning sequences
413-9-18	Types of cleaning mechanisms
413-9-19	Shaking for cleaning bags
413-9-20	Reverse air cleaning
413-9-21	Reverse jet--blow ring
413-9-22	Pressure jet or pulse jet cleaning
413-9-23	Pressure jet with use of venturi for cleaning bags
413-9-24	Woven fabric filter material
413-9-25	Felted fabric filter material
413-9-26	Types of fibers
413-9-27	Causes for bag failure
413-9-28	Pressure drop expression--across the fabric
413-9-29	Pressure loss due to the cake
413-9-30	Total pressure drop (across the filter and the cake)
413-9-31	Filter drag expression
413-9-32	Filter seiving mechanism
413-9-33	Filter cake--cake buildup
413-9-34	Performance curve--filter resistance versus the buildup of the cake

413-9-35	Overall pressure drop for a multi-component baghouse
413-9-36	Filtration velocity--air to cloth ratio
413-9-37	Air to cloth ratio--the delicate balance that affects the performance of the baghouse
413-9-38	Factors affecting baghouse performance
413-9-39	Gas conditioning--cooling
413-9-40	Review--collection mechanisms
413-9-41	Review--filtering designs
413-9-42	Review--collection mechanisms
413-9-43	Review

AIR POLLUTION TRAINING INSTITUTE

CONTENT OUTLINE

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

Course: 413 - Lesson 9
Lecture Title: FABRIC FILTER PRINCIPLES

Page 1 *of* 14

NOTES

I. Introduction
  - A. References -- pass out listing of references
  - B. Description -- baghouses are like huge vacuum cleaners to collect particulates with a high efficiency
    - 1. Baghouses also called fabric filter collectors, bag filters, fabric dust collectors, filter collectors, dust collectors, cloth collectors and filter houses.
    - 2. Types
      - a. disposable -- deep bed, panel, and mat filter are discarded rather than reused or cleaned. i.e. furnace or AC filter

Slide: 413-9-1

      - b. fabric filter -- where dust bearing gases are passed unidirectionally through a fabric which consists of:

NOTE:
point out collection hopper

        - (1) filter medium and support
        - (2) cleaning device
        - (3) dust collection hopper
        - (4) isolation closure - or housing
        - (5) prime gas mover - fans
        - (6) necessary sensing devices and operational controls

Slide: 413-9-2
NOTE: point out housing

    - 3. Two ways to operate the baghouse
      - a. Pushthrough - gases pushed through the collector - by fan
      - b. Pullthrough - gases pulled through the collector - fan on back side of baghouse - most baghouses designed this way can use backward curve blade fans, which are more efficient and also lessen the chance of particle damage to fan blades and bearings.
      - c. Advantages and disadvantages of pushthrough and pullthrough

II. Collection Mechanisms - way particles collected
  - A. Impaction - particles have too much inertia to follow streamlines around filter fiber and thus impact on the surface.

Slide: 413-9-3
Slide: 413-9-4
NOTE: usually account for 99.9% particles $> 1\mu$

CONTENT OUTLINE

Course: 413 - Lesson 9
Lecture Title: FABRIC FILTER PRINCIPLES

Page 2 **of** 14

NOTES

B. Interception - particles having very small inertia (smaller particles) can barely follow streamlines around obstruction. Particle is immersed in the viscous stream, slows down and touches the barrier (filter fiber or dust cake) and stops.

Slide: 413-9-5

C. Diffusion - important for particles that are below 1 um in aerodynamic diameter. Particles in the range of .1μ in diameter are in the Brownian motion range -- particles are so small their individual motion can be affected by collisons on a molecular or atomic level -- collection is a result of random motion causing interception with fiber or dust cake.

Slide: 413-9-6

Slide: 413-9-7

D. Gravitational settling and agglomeration - some particles - larger particles settle on initial entry.

Slide: 413-9-8

E. Electrostatic attraction - particles having a (+) or (-) charge attracted to cloth of the opposite charge - slight effect - sometimes referred to a triboelectric effect.

F. Other effects - particle agglomeration can be promoted by decrease in temp - shock cooling, i.e. shock cooling by water sprays, fine particles agglomerate together - must not let gas reach dew temp. and must keep relative humidity < than 90%.

III. Filtration Process

A. Systems

Slide: 413-9-9

1. Bottom feed - gases enter the bottom, directed into bags, filtered and exit through bags - clean air on outside of bag

Slide: 413-9-10

2. Top Feed - dust laden gases enter through the top of the baghouse filter tubes, filtered and exit through bags - clean air on outside of bag

3. Exterior filtration - gases pass from the outside of tubes (filter) to the inside or clean air side. This type of arrangement requires inner bag support

Slide: 413-9-11

B.

1. Bags - generally tubular in shape, vary in length and diameter 6" - 18" diameter up to 40 ft. long. Ratio of bag length to diameter generally from 4:1 to 16:1
2. Bags - hung or attached - depends on type of cleaning involved - but secured at either top or bottom or both, usually hang vertically, i.e.
    - * shaker hold at top and sheath at bottom
    - * some supported by inner cage

Slide: 413-9-12

NOTE: mention bag configurations

Slide: 413-9-13

C. Housing

1. Single units - all gases into single housed unit.
2. Compartmental units - consist of more than one compartment

Slide: 413-9-14
413-9-15

D. Hoppers to collect dust

1. Manual clean out
2. Screw conveyer
3. Rotary valves

Slide: 413-9-16

IV. Cleaning Mechanisms

A. Sequences

1. Intermittant - done on a demand basis - entire compartment is passed by (gases) and bags cleaned row by row, or simultaneously
    (a) used for batch processes
    (b) usually cleaned in low pressure mode such as shaking, or reverse air.
    (c) intermittant cleaned baghouse is shut down in between process batches
2. Periodic - sections are compartmented and cleaned alternating filtering - cleaning cycles, i.e. one compartment cleaning while other two filtering.
    (a) usually low pressure mode cleaning

Slide: 413-9-17

3. Continuous - fully automatic, high pressure cleaning methods, bags cleaned with compressed air, 2.3 sec., filtering process interrupted momentarily. The blast of air will oppose the flow of cleaned air through the bag i.e. A/C ratio may be 16:1, velocity from pulse jet may be 50 ft./min.
    - (a) bags supported by cages - dust cake is cracked and popped off the bags
    - (b) higher dust loading permitted
    - (c) larger A/C ratio - always a row of bags being cleaned somewhere in baghouse
    - (d) generally compartmentalized with (n + 1) extra to guard against failures.

B. Types of cleaning mechanisms

Slide: 413-9-18

1. Shaking - low energy process - (low filtering velocity 1-5 ft/sec) shaking cleaners hold bag at the top of the bag and shake the entire tube sheath at the bottom. Shaking can be horizontal concave upwards or downwards, vertical, 90° arc swing - oscillating flexing motion - involves top of bag moved back and forth creating in relatively flat arc causing ripples in filter bag dislodging dust.

Slide: 413-9-19

    - (a) greatest wear at top where support loop attaches
    - (b) not used for sticky dust - would have to shake too hard
    - (c) can not use glass bags

    Sonic cleaning - employs sound generator to produce low frequency sound, causing bags to vibrate gently, noise level barely discernable outside filter compartment

    - (d) used with heavy denser carbonaceous dusts

2. Reverse air

    Bag collapse - simply collapsing the bag by reversing the air flow in the entire compartment -- backwash

Slide: 413-9-20

    - (a) backwash can cause rapid deterioration due to frequent flexing and creasing

(b) However, many manufacturers of reverse air units are finding that bag life can be as high as three to four years on this type of filter in the coal fired boiler business and the metallurgical industry. All other things being equal bag life is generally a function of good low air-to-cloth ratio.

(c) utilize filter velocities 1:1 to 6:1

3. Reverse jets - travelling blow rings involves reversing air flow but not depend on bag collapsing - series of rings, 1 for each bag travel up and down bag blowing a stream of compressed air into the bag from outside. Bags are normally cleaned by rows.

Slide: 413-9-21

   (a) disadvantage of blow ring - mechanical linkage and individual air hose attachments required for each bag
   (b) high maintenance involved ∴ use is decreasing
   (c) another disadvantage - blow rings use low reverse air pressure ∴ felted bags cannot be cleaned adequately
   (d) filtration velocities as high as 15 ft/sec

4. Pressure jet or pulse jet
   (a) pulse jet - pressure jet
      - high pressure air jet to create a low pressure inside the bag and then transfer momentum to the clean air

Slide: 413-9-22

      - jet (1) stops normal filtering flow
         (2) developes a standing wave in fabric of the bag which mechanically induces cake disintegration and discharge
         (3) reverse air flow through the bag for complete fabric cleaning
      - felted fabric used and allows collection of fine particles
      - felted fabrics have high permeability in use to allow high air to cloth ratios

- pulse jet use individual air supplies (from a common header) above each bag.
- pressure wave must be able to travel to bottom of bag

(b) This type of baghouse represents the design of approximately 40-50% of all the new baghouses being installed in the United States.

(c) 1- improved jet - basically same as pulse jet but use an individual venturi lowered to and sealed to each bag. Venturi allow use of all high pressure air to be used to set up shock wave, preventing loss of air ∴ less compressed air

Slide: 413-9-23

2- most pulse jet baghouse units employ a venturi or some other protection from the direct blast of compressed air.

3- * A/C ratio 15:1 - 25:1
* Less maintenance because of no moving parts
* Only moving parts are solenoids and diaphrams on air control valves which can be all located outside the baghouse for easy maintenance
** improved bag life - up to 3 times longer than shaker, 5 times longer than bag collapse method

V. Fabric Filter Material

A. Construction - woven and felted

1. Woven

(a) fabrics have a definite long-range repeated pattern. Open spaces around fibers must be bridged by impaction and interception before true filtering surface is formed (cake)

Slide: 413-9-24

(b) used in low energy cleaning - shaker, bag collapse

(c) weaves

(1) simple 1 under and 1 over in both directions - not used real frequently

(2) twill weave goes over two and under 1 in one direction only - stronger and more durable

(3) Satin - over 1 and under 3 - very compact, can use fine yarn; give fabric less porosity

(4) different weaving patterns decrease open area between fiber intersection ∴

∴ influences both strength and permeability of the fabric

Permeability is the volume of air which can be passed through 1 ft^2 filter medium with a Δp of no more than .5 inches H_2O

2. Felted — composed of randomly oriented fibers, compressed into a mat and sealed to some loosely woven backing material — depend to lesser degree on initial dust deposits than woven.

Slide: 413-9-25

   (a) generally 2-3 times thicker than woven
   (b) more severe cleaning methods required
   (c) higher pressure drops
   (d) higher A/C ratios
   (e) can reduce the exhaust burden down to .005 gr/SCF
   (f) should not be used in high humidity especially if particles are hygroscopic to avoid clogging and binding of filter.
   (g) felted material sometimes napped — fuzz projecting at end of fabric, can be used to collect tarry particulates

B. Types of Fiber

1. Natural

   (a) cotton -- cheap, readily available
   - temperature is limitation → gases <180°F
   - also not recommended for high alkali or acids
   - used for abrasive blasting, rock crushing, conveying

   (b) wool -- used in metalurigical operations
   - resist acid attack
   - temperature limitation 220°F

2. Synthetics -- nylons, polyesters

   (a) nylon - relatively high initial cost
   - excellent resistance to abrasion, flexing and resistance to many chemicals
   - thermal restrictions to 220°F

   (b) dynel - acrylic fiber
   - has low moisture absorption, good strength
   - resist many chemicals, mildew, bacteria
   - temperature limitation 175°F

   (c) orlon and dacron
   - good chemical resistance - heat resistance
   - temperature limit 275°

   (d) teflon - flurocarbon $expensive$
   - used for high temperature gases
   - 450°F to 500°F
   - inert to most chemicals except Cl and Fl
   - flex and abrasion strength only fair

   (e) Nomex
   - good to excellent resistance to alkali attack
   - poor resistance to acid attack
   - good resistance to abrasion
   - can withstand temperatures to 400^{0}F
   - used quite frequently for bag material

Slide: 413-9-26

NOTE: Point out to students See page 6-21 Table 6.1.2.

3. Fiberglass
    - highest resistance to chemicals and heat
    - up to 530°F
    - low resistance to abrasion and crushing
    - filtering velocity less
    - ∴ cleaning cycle usually pulse jet

C. Failure Mechanisms -- distinct failure mechanisms affect fabric filters

1. Upper temperature limit of process exhaust pretreatment may or may not be feasible because of problems of hygroscopicity

Slide: 413-9-27

2. Abrasion -- can occur when:
    (a) bags rubbing against each other
    (b) traveling blow rings mechanism - slight juggling and rubbing each pass
    (c) support rings - filter contacts ring
    (d) attach points of bag at top or bottom
    (e) 25%/yr. replacement due to this wear
3. Chemical attack -- could occur when:
    (a) poor fiber selection
    (b) change in process (and thus exhaust) particularly temperature and dust composition - acid dew point reached etc.

VI. Design Variables

A. Pressure drop - most talked about variable

1. Pressure drop expressed as: pressure drop per unit area is a function of the characteristics of a particular filter medium.

2. In general measurement of the air flow through a fabric and the pressure drop is by Darcy's Law directly proportional to flow

(No particulates) $\Delta p_f = k_1 v_f$

where

Δp_f = pressure drop across the fabric usually expressed in inch of H_2O

k_1 = inch H_2O/ft.min.

k_1 = fabric resistance (inches H_2O) and is a function of gas viscosity and filter characteristics such as thickness and porosity (permeability)

v_f = filtration velocity (ft./min.)

(Say where going to get around to defining more specifically later)

Slide: 413-9-28
NOTE:
eq. 6.2.1 pressure drop across the fabric

NOTE:
Permeability is defined by ASTM standard - is the volume of air which can be passed through 1 ft.^{2} filter medium with ΔP of no more than .5 inches H_2O

3. Pressure drop across the cake:

For the filtration head loss through a dust cake formed on a fabric filtering particle laden air. Can be expressed in simplified form as:

$\Delta p_c = K_2 c_i v_f^2 t$

Δp_c = pressure loss across cake in H_2O

K_2 = resistance of cake $(\frac{lb.}{ft^2})\ (\frac{ft.}{min})$

c_i = dust loading (lb/ft.^{3})

t = filtration time (min.)

v_f = face velocity of gas at filter (fpm)

K_2 is the dust-fabric filter resistance coefficient and is determined experimentally. The coefficient is dependent on gas viscosity, particle density, and dust porosity.

Slide: 413-9-29

NOTE: eq. 6.2.3 in 413 manual

$\Delta p_T = \Delta p_f + \Delta p_c$

or

$\Delta p_T = K_1 v_f + K_2 c_i v_f t$

Slide: 413-9-30

NOTE:
Eq. 6.2.4 in 413 manual
This equation should only be used for shaker or reverse air cleaning baghouses.

B. Filter Resistance

1. Want to define the filter drag

   $S = \frac{\Delta p}{v_f}$ as the filter drag across the fabric - dust layer, and it is a function of the quantity of dust accumulated on the filter.

Slide: 413-9-31

NOTE:
$S = \frac{\Delta p}{v_f}$
v_f = filtration velocity

2. In industrial filtration - weave important. New fiber has considerable interfiber area - open. The true filtering surface is not the bag itself -- but the dust layer itself. The bag merely provides the mechanisms for coarse sieving to remove large particles by supporting the dust layer. Dust bridges the pores and the drag increases rapidly. The resistance to flow-filter drag $\Delta p/v_f$ is plotted versus the area cake density $p_i c_f t$ (weight/unit area of cloth)--see figure. Typically the curve is composed of two zones:
   - (a) the zone of cake repair
   - (b) the zone of homogeneous cake formation

Slide: 413-9-32

Slide: 413-9-33

Slide: 413-9-34

3. The drag increases until the total pressure drop reaches a value set by the system design for activation of the cleaning cycle. At this point pressure drop decreases (almost vertically on the preformance curve) to the initial point cake repair begins when the cleaning cycle ceases and the cycle repeats.

4. For multicompartment baghouses -- where compartments are cleaned one at a time. The preformance curve has a slight sawtooth shape for the net pressure losses across the entire baghouse. *Note the average value.

   In order to maintain high filtration rate and a high collection efficiency → must select a fabric and cleaning mechanism which gives a optimal preformance curve (decrease slope).

Slide: 413-9-35

(a) If we can minimize the residual drag

(b) Minimize the cake repair time ∴ the filtering surface will rapidly form, collector has a low pressure drop and the length of the time between cycles will be longer.

C. Performance Factor

1. Consistant pressure drop is a critical design factor. System Δp may be twice the total drag of the cake due to skin friction and form friction between emission source and baghouse effluent discharge. Could be as much as 2-4 in H_2O and should be considered when designing the system.

2. Filtering velocity $\bar{v}$, is defined as the actual volumetric gas flow rate Q divided by the filtering area A.

$$v = \frac{Q}{A}$$

This is the superficial filtering velocity or the air to cloth ratio which is expressed as a function of the pressure drop thru the fabric itself.

Slide: 413-9-36

NOTE: mention table 6.2.1, 6.2.2, 6.2.3, 6.2.4 give recommended filtering velocities

D. Collection Efficiency - High 99.9^+

1. Baghouse is only device that is not designed with use of fractional efficiency curves.

2. Baghouse designed and sized strictly on experience. - manufacturers can only guarantee to meet opacity regulations and to meet regulations (grain loading)

3. The manual gives an equation to find the efficiency (page 6-26 in manual). The equation uses (4) four empirical constants designated by the various manufacturers.

Ask question -- Does anyone know formula for efficiency design?

Note: 6.2.5

$N = (K_3-1)/K_3$

$K_3 = aL^b \rho C V_f^d$

Slide: 413-9-37

VII. Preformance Factors

A. Correct A/C Ratio -- the delicate balance

1. This is one of the most important factor in design of baghouses. Good air-to-cloth ratio is imperative for effective collection efficiency and can prevent premature bag failure and subsequent replacement.

a. Again the air to cloth ratio is a term commonly used to express the cubic feet per minute of air that can be passed through one square foot of cloth.

B. Performance factors

1. Balancing Form, Headers, Dampers
   - must be properly designed. Dampers used to change bulk gas from one compartment to another
2. Timing devices for cleaning -- filtering-cleaning cycle should be at least 10:1 or greater
3. Allow for dust removal various type of baghouses, i.e., pulse jet requires conveyers or rotating screws
   - size of hopper governed by dust loading, filtration volume and required dust removal rate.

NOTE: recommended filtering velocities Table 6.2.1
6.2.2
6.2.3
6.2.4
in 413 manual

Slide: 413-9-38

VIII. Gas Conditioning

A. Cooling - necessary sometimes

Slide: 413-9-39

1. Dilution - by air - cheapest, especially at high temperature - but higher air handled as a result of dilution requires larger baghouse - plus it is hard to control the intake of ambient moisture and control other contaminents
2. Radiation -- use of duct walls long uninsulated ducts. Ducts can also be U shaped.
   - Radiation below 1000°F requires substantial surface areas, lengthy duct runs, and increased fan horsepower.
   - Precise temperature control difficult to maintain - also there is a possibility of plugging by sedimentation.
3. Evaporative cooling -- injecting fine water droplets - droplets evaporate, absorbing heat from the gas.
   (a) add gaseous volume of H_2O to exhaust stream therefore bigger baghouse than with radiation
   (b) gives greatest amount of cooling at low installation cost.
   (c) temperature control flexible and precise

(d) must not let temperature go below the dew point of the gas - chemical attack

(e) must evaporate all H_2O before gases reach baghouse → to guard against corrosion and fabric plugging

4. Heat exchangers
5. Combination of all of the above

IX. Review:

The past 1 1/2 hour we have talked briefly about the following subjects

Slide: 413-9-40

- * Collection Mechanisms
  - impaction
  - direct interception
  - diffusion
  - gravitation

Slide: 413-9-41

  - electrostatic attraction
- * Various Filtering Designs

Slide: 413-9-42

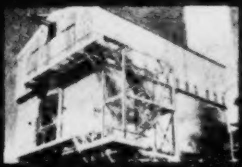
- * Cleaning Mechanisms
  - Shaking
  - Reverse air
  - Reverse jet; blow ring

Slide: 413-9-43

  - Pressure jet or pulse jet
- * Various fabrics used for baghouses
- * Pressure drop
- * Cake formation
- * Filtering velocity commonly referred to as air to cloth ratio.

DATE 6/80 ASSIGNMENT 413 L-9 NO. 10

1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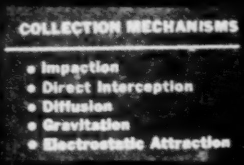
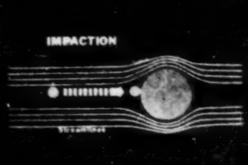

COLLECTION MECHANISMS

- Impaction
- Direct Interception
- Diffusion
- Gravitation
- Electrostatic Attraction

3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Streamlines
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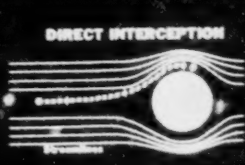
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Streamlines
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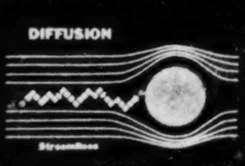
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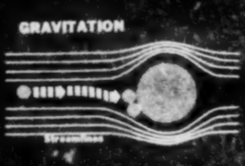
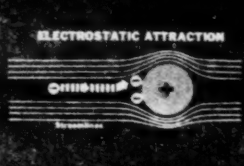
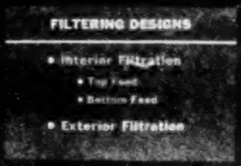
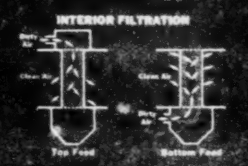

GRAVITATION
Streamlines
7

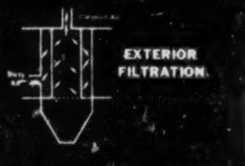

ELECTROSTATIC ATTRACTION
Streamlines
8


FILTERING DESIGNS

- Interior Filtration
  - Top Feed
  - Bottom Feed
- Exterior Filtration

9


INTERIOR FILTRATION
Dirty Air
Clean Air
Clean Air
Dirty Air
Top Feed
Bottom Feed
10


Clean Air
Dirty Air
EXTERIOR FILTRATION
11

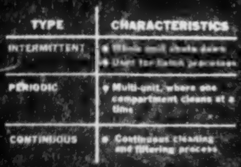
12

13

14

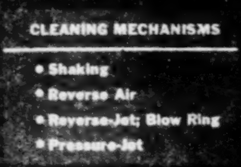
15

16



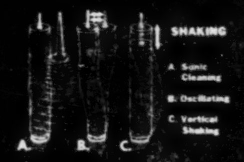
TYPE	CHARACTERISTICS
INTERMITTENT	• Whole unit shuts down • Used for batch processes
PERIODIC	• Multi-unit, where one compartment cleans at a time
CONTINUOUS	• Continuous cleaning and filtering process

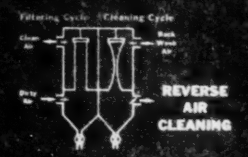
17

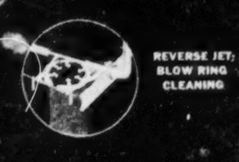

CLEANING MECHANISMS

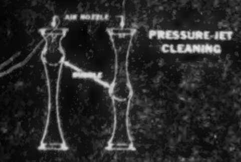
- Shaking
- Reverse Air
- Reverse-Jet; Blow Ring
- Pressure-Jet

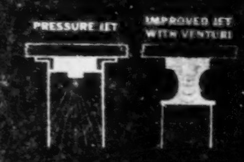
18

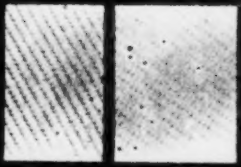

SHAKING
A. Sonic Cleaning
B. Oscillating
C. Vertical Shaking
A.
B.
C.
19


Filtering Cycle
Cleaning Cycle
Clean Air
Back Wash Air
Dirty Air
REVERSE AIR CLEANING
20

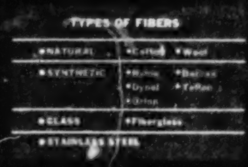

REVERSE JET; BLOW RING CLEANING
21


AIR NOZZLE
PRESSURE-JET CLEANING
22


PRESSURE JET
IMPROVED JET WITH VENTURI
23

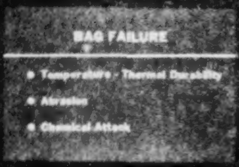

24

25


TYPES OF FIBERS

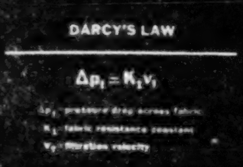
• NATURAL	• Cotton	• Wool
• SYNTHETIC	• Nylon • Dynel • Orlon	• Dacron • Teflon
• GLASS	• Fiberglass	
• STAINLESS STEEL		

26


BAG FAILURE

- Temperature - Thermal Durability
- Abrasion
- Chemical Attack

27


DARCY'S LAW

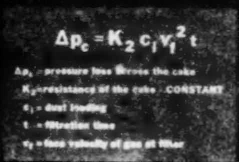
$$\Delta p_f = K_1 v_f$$

Δp_f = pressure drop across fabric

K_1 = fabric resistance constant

v_f = filtration velocity

28


$$\Delta p_c = K_2 c_i v_f^2 t$$

Δp_c = pressure loss across the cake

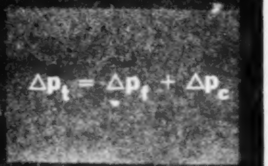
K_2 = resistance of the cake - CONSTANT

c_i = dust loading

t = filtration time

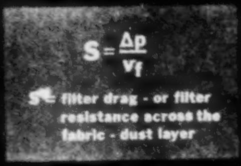
v_f = face velocity of gas at filter

29


$$\Delta p_t = \Delta p_f + \Delta p_c$$

30

DATE 6/80 ASSIGNMENT 413 L-9 NO.

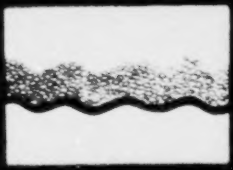


$$S = \frac{\Delta p}{v_f}$$

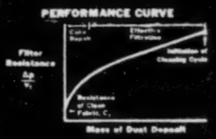
S = filter drag - or filter resistance across the fabric - dust layer

31

32

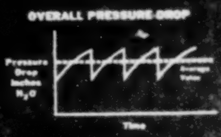


33



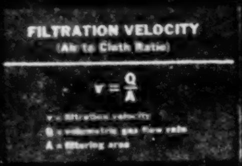
PERFORMANCE CURVE

34



OVERALL PRESSURE DROP

35

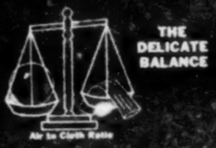


FILTRATION VELOCITY
(Air to Cloth Ratio)

$$v = \frac{Q}{A}$$

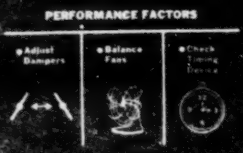
v = filtration velocity
Q = volumetric gas flow rate
A = filtering area

36



THE DELICATE BALANCE

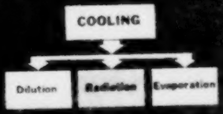
37



PERFORMANCE FACTORS

- Adjust Dampers
- Balance Fans
- Check Timing Device

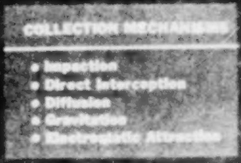
38



COOLING

Dilution | Radiation | Evaporation

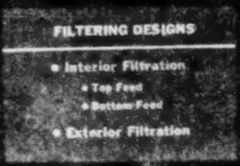
39



COLLECTION MECHANISMS

- Impaction
- Direct Interception
- Diffusion
- Gravitation
- Electrostatic Attraction

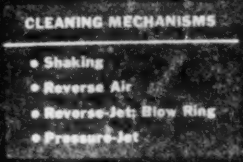
40



FILTERING DESIGNS

- Interior Filtration
  - Top Feed
  - Bottom Feed
- Exterior Filtration

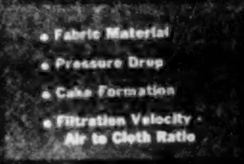
41



CLEANING MECHANISMS

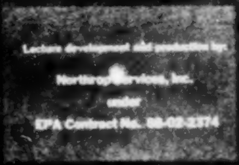
- Shaking
- Reverse Air
- Reverse-Jet; Blow Ring
- Pressure-Jet

42



- Fabric Material
- Pressure Drop
- Cake Formation
- Filtration Velocity - Air to Cloth Ratio

43



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under

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LESSON PLAN

AIR POLLUTION TRAINING INSTITUTE

TOPIC: FABRIC FILTER APPLICATIONS

COURSE: 413 - Lesson 10
LESSON TIME: 30 minutes
PREPARED BY: DATE 4/79
David S. Beachler

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

LECTURE GOAL: Briefly describe the design factors and criteria necessary for fabric filter particulate collection and the various applications where the use of a baghouse is and is not appropriate.

LECTURE OBJECTIVES: At the end of this lesson the students should be able to:

* Recall the advantages and disadvantages of using fabric filters for collection of particulates.
* Recall the important design factors that are basic to the design of the control system.
* Recognize the various industries where baghouses can be used to collect particulate emissions and those types (or classes) of sources for which baghouses are not suitable.

STUDENT PREREQUISITE SKILLS: Ability to understand basic principles of physical science and perform calculations using logathrithms and exponential functions.

LEVEL OF INSTRUCTION: Advanced

INTENDED STUDENT PROFESSIONAL BACKGROUND: Engineering or physical science

SUPPORT MATERIALS AND EQUIPMENT:

1. slide projector
2. overhead projector
3. chalkboard
4. 413 Student Manual

SPECIAL INSTRUCTIONS: The material concerning the use of fabric filters should be covered briefly, as the problems will take up most of the time. The author lists in the 413 Manual the various industries where fabric filters can be applied for particulate emission control. For additional information concerning emission sources and rates, control practices and equipment the student should refer to the reference listed below titled "Particulates and Fine Dust Removal" by Sittig.

REFERENCES:

1. 413 Student Manual
2. 413 Student Workbook pp. 20-24
3. "Air Pollution Control Technology, An Engineering Analysis Point of View", by Robert M. Bethea, Van Nostrand Reinhold Company, New York, 1978, pp. 145-208.
4. "Particulates and Fine Dust Removal", by Marshall Sittig, Noyes Data Corporation, Park Ridge, New Jersey, 1977.
5. "Procedures Manual for Fabric Filter Evaluation", EPA 600/7-78-113, IERL Research Triangle Park, N. C., June 1978.
6. "Proceedings The User and Fabric Filtration Equipment Specialty Conference", the Niagara Frontier Section, Air Pollution Control Association, Pittsburgh, PA, October 1973.
7. "Proceedings The User and Fabric Filtration II Equipment Specialty Conference", the Niagara Frontier Section, Air Pollution Control Association, Pittsburgh, PA, October 1975.
8. "Proceedings The User and Fabric Filtration III Equipment Specialty Conference", the Niagara Frontier Section, Air Pollution Control Association, Pittsburgh, PA, October 1978.
9. "Industrial Air Pollution Control Equipment for Particulates", by L. Theodore and A. J. Buonicore, CRC Press, Inc., Cleveland, OH, 1976.

10. "Handbook of Fabric Filter Technology. Vol. I. Fabric Filter Systems Study", Charles E. Billings, et. al., distributed by NTIS, PB-200-648, December, 1970.

11. "Appendices to Handbook of Fabric Filter Technology, Vol. II. Fabric Filter Systems Study", GCA Corporation, Bedford, Massachusetts, distributed by NTIS. PB-200-649, December 1970.

12. "Fabric Filter Cleaning Studies", EPA Technology Series, EPA 650/2-75-009, January 1975.

AUDIO-VISUAL MATERIALS FOR LESSON 10

Lesson 10 Fabric Filter Applications

413-10-1	Principal advantages
413-10-2	Principal advantages
413-10-3	Principal disadvantages
413-10-4	Principal disadvantages
413-10-5	Design factors
413-10-6	Design factors continued
413-10-7	Live shot of baghouse

CONTENT OUTLINE

Course: 413 - Lesson 10
Lecture Title: FABRIC FILTER APPLICATIONS

Page 1 of 4

NOTES

I.

A. Principal Advantages 413-10-1

1. Collection efficiency high -- 99.9% can reduce effluent down to .005 gr/SCF
2. Efficiency and pressure drop -- unaffected by changes in inlet loadings - cyclic process rates
3. Filtered air can be recirculated within plant -- heating purposes (if gases are not toxic)
4. Collected material dry for subsequent disposal or reprocessing
5. Eliminates major H_2O pollution problems, liquid waste or liquid freezing
6. Corrosion and rusting of components usually no problem 413-10-2
7. No hazzard of high voltage -- simplifying maintanence and repair -- and permitting collection of flammable dusts
8. Low initial costs -- compared to ESP and scrubbers
9. Moderate power comsumption

B. Principal Disadvantages 413-10-3

1. Large size -- installation space
2. High maintenance requirement -- broken bags difficult to detect
3. Fabric life can be shortened by acidic or alkaline particle or gas constituent
4. Upper temperature limit -- some filters will operate in 550°F range
5. Hygroscopic materials, condensation of moisture or tarry adhesive components may cause crusty caking or plugging of the fabric or require special additives 413-10-4

6. Concentrations of some dusts in the collector may represent a fire or explosion hazzard if spark or flame is admitted by accident. Fabrics will thus burn.
7. Fabric must maintain mechanical durability -- tensile and flex strength. *Bag life is simple most important problem
8. Replacement of fabric (bags) may require respiratory protection for maintenance personnel.

II. Name the important design factors that must be considered when designing a baghouse for emission control of a specific process. 413-10-5

1. Space restrictions
2. Method of cleaning - shaking, reverse air, pulse jet
3. Use of negative or positive system - toxic materials require negative
4. Construction of system - field, shop, modular, panel, compartment
5. Types of fabrics - natural, synthetic, glass
6. Air to cloth ratio
7. Need for gas cooling or preconditioning 413-10-6
8. Provision for maintenance and access--one must be able to get to bags for replacement.
9. Problem of emission capture - hoods, ducts, fans
10. Material handling equipment - hoppers, screw conveyers, dust removal, etc.
11. Effluent discharge - stack, single or double
12. Electrical controls - for cleaning mechanisms, etc. from a single timed cycle to one that cleans when Δp is at design level.

III. Design Criteria

The principal design criterion is the gas flow rate, measured in actual cubic feet per min. ACFM. The volume to be treated is fixed by the process (source) but the filtration velocity or air to cloth is up to the designers.

A. The velocity depends on:

1. Dust loading

2. Type, shape and density of dust
3. Type of fabric - natural, synthetic, etc.
4. Fabric construction - woven or nonwoven, thickness of fabric, fiber size, fiber density - fibers/area^2, napping, allowable pressure drop before initiation of cleaning, residual drag of freshly cleaned medium
5. Cleaning method - high ΔP cleaning methods (pulse jet) allows high A/C ratio
6. Amount of flexing and creasing is a result of cleaning - higher A/C causes more cleaning thus more flexing and creasing
7. Fraction of bags out of service due to leaks

B. Cleaning time
   1. Ratios of filtering time to cleaning time is the measure of the % of time filter is performing effectively should be at least 10:1 or greater

C. Power requirement - keep pressure drop low - by minimizing residual drag C_r

D. Bag spacing important -- there must be enough room for proper inspection of bag failures.

E. Allowance for proper cleaning of bags - N + 1 components
   1. Allow reserve capacity for off-line cleaning
   2. Inspection and maintenance for broken bags

IV. Selected applications - fabric filter applications are as varied as the type of systems and the fabrics available Some possible uses for baghouse in industry are:

413-10-7

1. Steel industry:
   - Electric arc furnaces
   - Open hearth furnaces

   > cooling first

   - Boiler operations
2. Foundry cupolas:
   - Gases cooled from +1000°F to 500°F
3. Nonferrous metal furnaces:
   - Lead
   - Copper smelters
   - Zinc

CONTENT OUTLINE

Course: 413 - Lesson 10
Lecture Title: FABRIC FILTER APPLICATIONS

NOTES

4. Grain handling operations:
   - Cleaning
   - Handling
   - Grinding
   - Blending

Must be careful not to permit baghouse to reach explosive concentrations.

5. Chemical industry:
   - Dryers
   - Grinding mills
6. Carbon black plants
   - Gases must first be cooled (steam injection)
   - Carbon black generated by burning oil or tar in furnaces and collecting the dust load
7. Cement kilns:
   - Collection of dust from rotary cement kilm
8. Power plants:
   - Successful operation on the Sudbury Power Plant, PA. 175 mw.
   - Nucela Station - Colorado
9. There is a table in the 413 Manual that lists some selected fabric filter applications, and lists such variables as:
   * Dust type - process name
   * Efficiency
   * Average particle size
   * Inlet temperatures
   * A/C ratio
   * Pressure difference ΔP
   * Cloth type

Point out Table 6.3.1

10. Mention sources that a baghouse would not be appropriate.
    a. liquid or water-laden gaseous streams
    b. high temperature gas streams where proper cooling was not economically feasible. (open hearth or basic oxygen furnaces)

INSERT FILM EMULSION SIDE DOWN

DATE 6/80 ASSIGNMENT 413 L-10 NO 12

ADVANTAGES

1

ADVANTAGES (Cont.)

2

DISADVANTAGES

3

DISADVANTAGES (Cont.)

4

DESIGN FACTORS

5

DESIGN FACTORS (Cont.)

- Gas Preconditioning
- Maintenance and Access
- Emission Analyses
- Material Handling Equipment
- Effluent Discharge
- Electrical Controls

6

7

Lecture developed and production by:

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under

EPA Contract No. 68-02-2374

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Fabric Filter Applications

Technical Content: David Beachler

Instructional Design: [illegible]

Graphics: [illegible]

Photography: Craig Mann

9

LESSON PLAN

AIR POLLUTION TRAINING INSTITUTE

TOPIC: PROBLEM SESSION VI
FABRIC FILTERS

COURSE: 413 - Lesson 10a
LESSON TIME: 1 hour
PREPARED BY: DATE: 6/79
David Beachler

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

LESSON GOAL:	Briefly describe the use of the pressure drop and collection efficiency formulas covered in the Fabric Filter lessons by solving four problems.
SUPPORT MATERIALS AND EQUIPMENT	1. Chalkboard 2. 413 Student Workbook pp. 20-24.

CONTENT OUTLINE

Course: 413 - Lesson 10a
Lecture Title: FABRIC FILTERS - PROBLEM SESSION VI

Page 1 of 6

NOTES

I. Problem 6-1

A. Work out problem 6-1 for students. The solution for 6-1 is:

NOTE: See problem 6-1 on page 20 of the 413 Student Workbook.

6.1 Fabric Filters — Number of Bag Calculation

Small scale tests showed that filtration of an air stream containing one grain of particulates per cubic foot of air gave a maximum pressure drop of 5 inches of water at a flow rate of 3 ft^3/min per square foot of filtering surface .

- **a. Calculate the horsepower required for a fan for a flow rate of 6,000 ft^3/min. through the baghouse.**
- **b. Calculate the number of 0.5 ft diameter by 10 ft filtering bags required for the system.**

Assume an over-all fan-motor efficiency of 63%.

SOLUTION:

(a) $$hp = \frac{\begin{bmatrix}\text{flow rate}\\ \text{CFM}\end{bmatrix} \times \left[\Delta p \text{ inches } H_2O\right] \left[1.575 \times 10^{-4}\right]}{\text{efficiency (fan)}}$$ (Chemical Engr. Handbook)

$$hp = \frac{\left(6000 \frac{ft^3}{min}\right) \times \left[5 \text{ inches } H_2O\right] \times \left[1.575 \times 10^{-4}\right]}{.63}$$

$$hp = 7.5$$

(b) Area of Bag = $2\pi rH$ or $\underline{\pi DH}$

$= (3.14)(.5 \text{ ft})(10 \text{ ft})$

$= 15.7 \text{ ft}^2$

Total filtering area = $\dfrac{6000 \text{ ft}^3/\text{min}}{3 \text{ ft}^3/\text{min} \big/ \text{ft}^2 \text{ flitering surface}}$

$= 2000 \text{ ft}^2$ (filtering surface)

# bags required = $\dfrac{\text{filtering surface}}{\text{area/bag}} = \dfrac{2000 \text{ ft}^3}{15.7 \text{ ft}^2/\text{bag}}$

= 128 bags

II. Problem 6-2

A. Work out problem 6-2 for the students

B. The solution for problem 6-2 is:

NOTE: See problem 6-2 on page 21 in the 413 Student Workbook

6.2 Fabric Filters - Number of Bags and Pressure Drop

A plywood mill plans to install a fabric filter as an air cleaning device.

a. How many bags, each 8 inches in diameter and 12 ft long, must be used to treat the exhaust gas which has a particulate loading of 2 grains/ft^3 and the exhaust fan is rated at 7,000 ft^3/min?

b. If the pressure drop is given by the formula

$$\Delta p = \Delta p_{\substack{\text{clean}\\\text{fabric}}} + \Delta p_{\substack{\text{dust}\\\text{cake}}}$$

Estimate the pressure drop after four hours of operation if the resistance coefficients of the filter and dust cake are, respectively, K_1 = 0.8 inches water/ft min. and K_2 = 3 inches water/(lb/dust/ft^2 cloth area)(ft/min, filtering velocity). Assume velocity is 2 ft/min.

SOLUTION:

(a) With 2 ft/min as the filtration velocity

(1) Total area required $= \dfrac{7000\ \text{ft}^3/\text{min}}{2\ \text{ft/min}} = 3500\ \text{ft}^2$

(2) Area of each Bag $= \pi\ D\ H$

$$= (3.14)\left(\frac{8\ \text{in.}}{12\ \text{in/ft}}\right) \times 12\ \text{ft}$$

$$= 25.13\ \text{ft}^2 / \text{bag}$$

(3) # bags required =

$$\frac{\text{Total Area}}{\text{area ea. bag}} = \frac{3500\ \text{ft}^2}{25.13} = 139\ \text{bags}$$

(b) The pressure drop is given by the following realtionships

$$\Delta p = \Delta p \ \substack{\text{clean}\\\text{fabric}} + \Delta p\ \text{(of dust cake)}$$

$$\Delta p = k_1 v + k_2\ c_1\ v^2 t$$

$$= \left(\frac{.8\ \text{inches H}_2\text{O}}{\text{ft-min}}\right)\left(2\text{ft/min}\right) + \frac{3\ \text{inches H}_2\text{O}}{\text{lb dust/ft}^2\text{(ft/min)}} \times \frac{\frac{2\ \text{grains}}{\text{ft}^3}}{7000\ \frac{\text{gr}}{\text{lb}}} \times \left(2\ \frac{\text{ft}}{\text{min}}\right)^2 \times 4\ \text{hr} \times 60\ \frac{\text{min}}{\text{hr}}$$

Δp = 2.42 in H_2O

III. Problem 6-3

A. Have students work problem 6-3 on page 22 of the 413 Problem Workbook

B. Allow the students 10 minutes to solve the problem; then go over the solution. The solution to 6-3 is:

NOTE: See problem 6-3 on page 22 of the 413 Student Workbook

6.3 Fabric Filters — Number of Bags and Cleaning Frequency

A plant emits 50,000 acfm of gas with a dust loading of 5 grains/ft^3. The dust is collected by a fabric filter at 98% efficiency when the average filtration velocity is 10 ft/min. The pressure drop is given by

$$\Delta p = 0.2v + 5c_1v^2t$$

where:

Δp is the pressure drop in inches of water,
v is the filtration velocity in ft/min,
c_1 is the dust concentration in lb/ft^3 of gas,
t is the time in minutes since bags were cleaned.

a. How many cylindrical bags, 1 ft in diameter and 15 ft high will be needed?

b. The system is designed to begin cleaning when the pressure drop reaches 8 inches of water. How frequently should the bags be cleaned?

SOLUTION:

(a) The required surface area of the bags is

$$\text{Total area} = \frac{50{,}000\ \text{ft}^3/\text{min}}{10\ \text{ft/min}} = 5000\ \text{ft}^2$$

$$\begin{aligned}\text{area of each bag} &= \pi D H \\ &= 3.14 \times 1\ \text{ft} \times 15\ \text{ft} \\ &= 47.12\ \text{ft}^2/\text{bag}\end{aligned}$$

Number of bags needed

$$= \frac{5000}{47.12} = 106\ \text{bags}$$

(b) $\Delta p = .2v + 5\ c_1\ v^2t$

$$t = \frac{\Delta p - .2v}{5\ c_1\ v^2}$$

$$t = \frac{8\ \text{inches H}_2\text{O} - \dfrac{.2\ \text{in. H}_2\text{O}}{\text{ft/min}} \times \dfrac{10\ \text{ft}}{\text{min}}}{\left(\dfrac{5\ \text{in. H}_2\text{O}}{\dfrac{\text{lb dust}}{\text{ft}^2} \times \dfrac{\text{ft}}{\text{min}}}\right) \times \left(\dfrac{5\text{gr/ft}^3}{7000\ \text{gr/lb}}\right) \times \left(10\dfrac{\text{ft}}{\text{min}}\right)^2}$$

t = 16.8 min. between cleaning

IV. Problem 6-4

A. Have students work problem 6-4 on page 24 of the 413 Problem Workbook.

B. Allow the students 10 minutes to solve the problem; then go over the solution with the student. The solution to 6-4 is:

(See following sheets)

NOTE: See problem 6-4 on page 24 of the 413 Student Workbook

6.4 Fabric Filters — Design of Filter Bag

It is proposed to install a pulse-jet fabric filter system to clean a 10,000 scfm air stream at 250°F, containing 4 grains/ft^3 of pollutant. For a 99% efficiency, the average air-to-cloth ratio is 2.5 cfm/ft^2 cloth. The following information, given by filter bag manufacturers, is available at the beginning of the selection process:

Filter Bag	A	B	C	D
Tensile Strength	Excellent	Above Average	Fair	Excellent
Recommended Maximum Operation Temperature, °F	260	275	260	220
Resistance Factor	0.9	1.0	0.5	0.9
Relative Cost Per Bag	2.6	3.8	1.0	2.0
Standard Size	8" x 16'	10" x 16'	1" x 16'	1' x 20'

a. Determine the filtering area required for this operation.

b. Based on the required area and the above information, select the most suitable filter bag and calculate the number of them that should be used. The proposal of a pulsed jet device using strong forces to clean the bags necessitates the selection of a fabric with at least above average tensile strength.

SOLUTION:

(a) $$A = \frac{\text{ACFM}}{\text{CFM/ft}^3 \text{ cloth or ft/min}}$$

Must change SCFM to ACFM

$$= (10{,}000 \text{ SCFM}) \times \frac{250^{\circ} + 460}{520} = 13{,}654 \text{ ACFM}$$

$$A = \frac{13{,}654 \text{ ft}^3/\text{min}}{2.5 \frac{\text{ft}^3}{\text{min/ft}^2} \text{ or (ft/min)}} = 5462 \text{ ft}^2$$

(b) The temperature of the gas stream is 250°F. Material D can't be used because it shows a maximum bag temp of 220°F.

Since a pulsed jet unit is being used and requires a selection of fabric with at least above average tensile strength, material C can be eliminated

Therefore A and B should be considered.

6.4 (b) cont'd

Area/bag = π D H

$$= (3.14)\left(\frac{8\text{ in}}{12\text{ in/ft}}\right)(16) = 34\text{ ft}^2\text{/bag}$$ - Filter Bag A

$$= 3.14\left(\frac{10}{12}\right)(16) = 42\text{ ft}^2\text{/bag}$$ - Filter Bag B

#/bags A = 5462/34

B = 5462/42

Filter Bag	Area/bag ft^2	# bags	cost/bag	Relative Cost
A	34	161	(2.6)	418
B	42	130	(3.8)	494

Based on calculations the choice would be filter A because of its lower relative cost.

and 161 bags are required.

LESSON PLAN

AIR POLLUTION TRAINING INSTITUTE

TOPIC: WET COLLECTOR THEORY

COURSE: 413 - Lesson 11
LESSON TIME: 1½ hour
PREPARED BY: J. A. Jahnke
DATE: 3/14/79

UNITED STATES · ENVIRONMENTAL PROTECTION AGENCY

LESSON GOAL: To present the hydrodynamic principles occurring in wet collector applications and to introduce the various methods used to estimate collection efficiency from such systems.

LESSON OBJECTIVES: The student will be able to:

* List the dominant physical mechanisms involved in wet scrubbing.
* Describe the relative effect of particle size, relative velocity and droplet size on the dimensionless "separation numbers" (target efficiency) for each mechanism.
* Calculate the average droplet size of a gas atomized spray using the Nukiyama-Tanasawa relation.
* Define the terms, "inertial impaction parameter," "penetration," "liquid to gas ratio," and "transfer unit."
* Calculate the collection efficiency for a venturi scrubber using the Johnstone correlation.
* State the "cut-power" rule developed by Calvert and give the assumptions associated with the rule.
* Calculate the penetration associated with a given particle cut diameter and scrubber type using the cut power rule.

* State the fundamental assumption associated with the contact-power rule.
* Calculate the efficiency of a scrubber by the contact-power rule, given the appropriate input parameters.
* Discuss the use of pilot plants for the selection and evaluation of wet scrubber systems.

STUDENT PREREQUISITE SKILLS: Ability to understand basic physical science principals and perform calculations with logarithms and exponential functions

LEVEL OF INSTRUCTION: Advanced

INTENDED STUDENT PROFESSIONAL BACKGROUND: High school math and general science. Understanding of first day's course lecture material

SUPPORT MATERIALS AND EQUIPMENT:

1. overhead projector
2. slide projector
3. chalk board
4. 413 Student Manual

SPECIAL INSTRUCTIONS: This is a rather involved lecture. The students, however, should not be made to feel lost since most of the equations are empirical in nature. A detailed understanding of the theoretical bases behind the efficiency correlations is not within the scope of the course and is not of particular interest to the students in any case.

The central point of the lecture is to present the empirical expressions currently in vogue for the calculation of particulate collection efficiency for wet scrubbers. Since the contact power rule is most commonly used in industry, it should receive the major emphasis in the lecture.

The lecturer may wish to combine the problem session with this lecture, breaking up the lecture by introducing appropriate problems after the discussion of each theoretical approach.

REFERENCES:

1. 413 Student Manual
2. Calvert, S., "How to Choose a Particulate Scrubber," Chemical Engineering, August 29, 1977, pp. 54-68.
3. Semrau, K. T., "Practical Process Design of Particulate Scrubbers", Chemical Engineering, September 26, 1977, pp. 87-91 (and references therein).
4. McIlvaine, R. W., "When to Pilot and When to Use Theoretical Predictions of Required Venturi Pressure Drop." APCA paper #77-17.1 70th Annual Meeting of APCA, Toronto, Ontario, June 20-24, 1977.
5. Perry, R. H. and Chilton, C. H., Chemical Engineer's Handbook Fifth Edition, 1973, McGraw-Hill, N.Y., pp. 20-94 - 20-97.
6. Kashdan, E. R. and Ranade, M. B., "Design Guidelines for an Optimum Scrubber System", EPA-600/7-79-018, Jan. 1979.

AUDIO-VISUAL MATERIALS FOR LESSON 11

Lesson 11 Wet Collector Theory

413-11-1	Wet collector theory--topics to be covered
413-11-2	Wet collector theory--collection mechanisms
413-11-3	Contact zone and separation zone
413-11-4	Advantages for using scrubbers
413-11-5	Advantages for using scrubbers
413-11-6	Disadvantages of scrubbers
413-11-7	Forces used in collection equipment
413-11-8	Direct interception
413-11-9	Impaction
413-11-10	Diffusion
413-11-11	Dominant collection mechanisms--direct interception and diffusion
413-11-12	Separation number or impaction parameter
413-11-13	Target efficiency--defined
413-11-14	Collection probability
413-11-15	Estimation of target efficiency
413-11-16	General target efficiency for direct interception
413-11-17	Impaction parameter for inertial impaction
413-11-18	Target efficiency for diffusion
413-11-19	Diffusion collection mechanism important--graph of collection efficiency versus particle size
413-11-20	Johnstone equation
413-11-21	Johnstone equation for venturi collection efficiency
413-11-22	Japanese literature search
413-11-23	Estimating d_o from the Nukiyama-Tanasawa relationship
413-11-24	Cut power theory--an emperical approach
413-11-25	Particle penetration
413-11-26	Cut diameter definition
413-11-27	Graph cut diameter versus physical size of particle
413-11-28	Cut power rule expression
413-11-29	Performance cut-diameter plot
413-11-30	Scrubber selection plot--cut power relationship for gas atomized spray scrubbers

413-11-31	Contact power
413-11-32	Wet collector theory--contact power
413-11-33	Fundamental assumption of contact power theory
413-11-34	Number of transfer units
413-11-35	Relation of efficiency to number of transfer units
413-11-36	Total pressure loss expression: P_T
413-11-37	Gas pressure drop
413-11-38	Power derived from liquid stream
413-11-39	Total pressure loss equation
413-11-40	Relationship between transfer units and contacting power
413-11-41	Wet collector theory--pilot systems
413-11-42	Methods for predicting venturi scrubber pressure requirements

CONTENT OUTLINE

NOTES

Course: 413 - Lesson 11
Lecture Title: WET COLLECTOR THEORY

I. Introduction

Slide:413- 11-1

NOTE: An expert could spend a day on each of these topics. Here you have 1¼ hour to do all five. Good Luck!

A. The device in general

1. The scrubber is a device using a liquid for removing substances from a gas stream.
2. Can remove both gaseous and particulate matter.
3. Have many different types of scrubbers (low / medium / high energy) (like in a Chinese restaurant - have many choices, but only a small number of basic ingredients).
4. In a wet scrubber, aerosol particles are confronted with "impaction" targets → can be wetted surfaces or individual droplets.

413- 11-2

Chem Eng. Calvert p. 55

5. Therefore, have a contact zone and a separation zone.

413- 11-3

6. Scrubbers have advantages and disadvantages

413- 11-4

a. Some Relative Advantages
- No secondary dust sources
- Small space requirements
- Ability to collect gas as well as particulate
- Ability to handle high temperature, high humidity gas streams.
- Ability to humidify a gas stream
- Fire and explosion hazard at a minimum

413- 11-5

b. Some Relative Disadvantages

413-11-6

- Corrosion problems
- Ability to humidify a gas stream (meteorological)
- Pressure drop and power requirement
- Water pollution
- Difficulty of by-product recovery

II. Mechanisms involved in wet collection

Describe mechanisms first

A. Note = will get to specific scrubber designs later in the afternoon, first want to understand some of the principles

413- 11-7

B. Possible Mechanisms
   1. Gravitational Force
   2. Centrifugal Force
   3. Inertial Impaction
   4. Direct Interception
   5. Diffusion
   6. Electrostatic Force

C. Dominant Mechanisms for particle - droplet interception — Slide:413- 11-8
   1. Direct Interception
      > 100 μm becomes important as $\frac{d_p}{d_o} \to 1$ Where d_p is particle diameter
      in general $d_{o\ min} \sim 50_\mu$ — d_o is droplet diameter
      but $d_p < 5$
   2. Inertial Impaction - Most scrubbers designed to utilize this mechanism — 413-11-9
      >1 μm (impingement)
   3. Diffusion (Brownian Motion) — 413-11-10
      Important only < .5 μm
   4. Dominant Mechanisms $\left\langle \begin{array}{l}\text{Inertial impaction}\\ \text{Diffusion}\end{array}\right.$ — 413-11-11

D. Separation Number:
   Associated with these mechanisms, have a dimensionless group called the "separation number", "impaction parameter" — 413-11-12

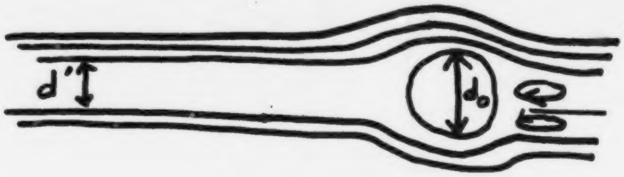
E. This is related to the "target efficiency" for one obstacle (drop) for a given particle size.
   1. Defined -- the percentage of particles in the total cross-section swept out by the droplet, that will be collected by the droplet. — 413-11-13

      or

      the ratio of the cross-sectional area of the gas stream cleaned of particles (all of which are alike) to the projected area of the obstacle.

2.

Slide 413-11-14



define a distance d' (depends on particle diameter). If the initial position of the particle (diameter d_p), is within $\pm \frac{d'}{2}$, it will be collected. If it's magnitude is greater than d'/2, it will escape impingement

For large particles, $>d_p$ $>d'$

as d_p increases, will reach a point where $d'/d_o \rightarrow 1$

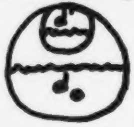
If d_p decreases, particle behaves more like a gas molecule and will diverge and not impinge

$$\frac{d'}{d_o} \rightarrow 0 \qquad \left(\begin{array}{l}\text{interested at most,}\\ \text{where } d_p \sim .1\ d_o\end{array}\right)$$

3. Quantitative Estimation of target efficiency η_I

413-11-15

$$\eta_I = \left(\frac{d'}{d_o}\right)^2 =$$



$$= \frac{\text{Area swept clean}}{\text{collection area}}$$

η_I a fcn of particle diameter, just as d' was.

4. Now d' is a nebulous thing → it is characterized in terms of the collection mechanism. For each collection mechanism is associated an impaction parameter -- Target efficiencies are analytically and experimentally correlated with the impaction parameter

413-11-16

a. Direct interception

$$\Psi = \frac{d_p}{d_o} \qquad \text{and} \qquad \eta_I = f\left(\frac{d_p}{d_o}\right)$$

Where η_I is the fractional collection efficiency of particles of size d_p by drops of size d_o

NOTE: $\eta_I = f\left(\frac{d_p}{d_o}\right)$

η_I is a function of the quantity $\frac{d_p}{d_o}$

b. Inertial impaction - (derived from continuum mechanics Stoke's Law considerations) constant particle density

$$\Psi_I = \frac{K \rho d_p^2 v_G}{18 \mu d_o} \qquad \eta_I = f(\Psi_I)$$

gas velocity at venturi throat

gas viscosity drop diameter

413-11-17

want small collector, high relative velocity, large particles. (Venturi's are efficient because they have a high relative velocity)

c. Diffusion

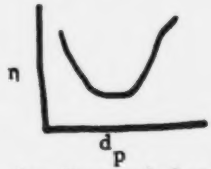
$$\Psi = \frac{RT}{\mu g\, v_{p/o}\, d_o\, d_p} \qquad \eta_D = \sqrt{\frac{k\,\tau}{\mu g\, v_{p/o}\, d_o d_p}}$$

413-11-18

down to 2-3μ size particles, continuum mechanics breaks down, talk instead of kinetics

$\eta_D = \left(\frac{d'}{d_o}\right)^2$ no longer has physical meaning, but is defined the same way for convenience

Note, when diffusion becomes important efficiency increases with decreasing particle size



413-11-19

III. Johnstone Equation for Venturi Scrubbers

Equation developed for estimating Venturi Scrubber efficiency → are many others, most have empirical constants.

An attempt to describe scrubber performance from basic mechanisms

In any wet scrubber, have a number of collecting particles. Have to generalize from a single collector to a number of collectors.

The derivation from this point to the Johnstone expression is optional. It should only be given if you have an attentive class. A group of non-engineers will be lost from the start.

Exposure 1

Fraction Captured	Fraction Escaped
η_I	$1 - \eta_I$

Exposure 2

Fraction Captured	Fraction Escaped
$\eta_I (1 - \eta_I)$	$(1 - \eta_I) - \eta_I (1 - \eta_I)$

Exposure 3

$$\eta_I \left[1 - \eta_I - \eta_I (1 - \eta_I)\right] \qquad 1 - \eta_I - \eta_I (1 - \eta_I) - \eta_I \left[1 - \eta_I - \eta_I (1 - \eta_I)\right]$$

or

$$(1 - \eta_I)(1 - \eta_I)(1 - \eta_I)$$

$$(1 - \eta_I)^3$$

Generalizing

get $(1 - \eta_I)^{S_o}$ where S_o is the number of exposures

In General:

$$e^{-x} = 1 - x + \frac{x^2}{2!} - \frac{x^3}{3!} \cdots$$

for small x $e^{-x} \sim 1 - x$

so $(1 - \eta_I)^{S_o} = e^{-\eta_I S_o}$

Total efficiency is then

$$\eta_p = 1 - e^{-S_o \eta_I}$$

generally don't know S_o → depends upon type of scrubber.

Note that η_I is a function of particle size and is quantitatively described in terms of the collection mechanisms given in II of this lecture.

For a venturi

$$\eta = 1 - e^{-k \frac{Q_L}{Q_G} \sqrt{\Psi_1}}$$

where $\Psi_I = \frac{C \rho v d_p^2}{18\, d_o\, \mu}$

d_o is estimated from the Nukiyama-Tanasawa relationship for droplet size from high-pressure atomization.

413-11-20

See page 5-44 of Manual

413-11-21

Johnstone came up with this semi-empirical expression using the concepts of II-4 and the expression $\eta_p = 1 - e^{-S_o \eta_I}$

413-11-22

413-11-23

$$d_o = \frac{1,920}{v_L}\left(\frac{\sigma}{\rho_L}\right)^{\frac{1}{2}} + 597\left(\frac{\mu_L}{\sqrt{\sigma\rho_L}}\right)^{.45}\left(1,000\frac{Q_L}{Q_G}\right)^{3/2}$$

Note that Johnstone eq. has limitations -- there are other approaches made by other people

For a venturi

$$d_o = \frac{16,400}{v_G} + 1.45 \frac{Q_L}{Q_G}^{1.5}$$

v_g = gas velocity at venturi throat (ft/sec)

$\frac{Q_L}{Q_G}$ = ratio of liquid-to-gas flow rates (gal/1,000 ft^3)

413-11-24

IV. Cut-Power Rule

(Another way of describing scrubber efficiency - more general than the Johnstone formalism)

An empirical approach

A. Introduction

1. A semi-theoretical approach - general approach given by Calvert

2. Relates scrubber fractional efficiency to power consumption. Estimates scrubber performance

See Calvert

Chem. Eng.
p. 54-68
August 29, 1977

B. Definition necessary for understanding "Cut-Power" Rule

1. Particle Penetration (Pt)

413-11-25

$$Pt = \frac{c_o}{c_i} = \frac{\text{Outlet particle concentration}}{\text{Inlet particle concentration}}$$

note, efficiency

$$\eta = 1 - Pt = 1 - \frac{c_o}{c_i} = \frac{c_i - c_o}{c_i}$$

413-11-26

2. "Cut diameter" (d_{pa})

Review:

Cut diameter = diameter of particle which is collected at 50% efficiency

Figure 413-11-27

$$d_{pa} = \sqrt{\rho_p \; C} \quad d_p$$

physical particle size

Particle Density

Cunningham correction factor

Aerodynamics diameter

3. Define

   d_{RC} as the cut diameter required for a specific application.

   i.e., the diameter of the particle which must be collected at 50% efficiency to obtain desired scrubber operation.

Note: This should have been given in 1st day lecture. May need to review.

4. Define

   d_{pg} Geometric-mean particle diameter

5. Define

   σg standard geometric deviation of the particle size distribution.

C. The "Cut-Power" Rule

(a) Most scrubbers, where collection is by inertial impaction, follow the exponential relation.

$$Pt_i = \left(\frac{c_o}{c_i}\right)_i = \exp\left(-Adpa_i^{\beta}\right)$$

413-11-28

Where i = i^{th} particle size

A = constant depending primarily on the liquid to gas ratio, droplet size, and particle density.

B = a constant which may be taken as 2.0 for most inertial wet scrubbers.

(Get fractional efficiency curve)

(b) Integrating this over the particle size distribution (assuming a lognormal distribution), obtain the performance cut-diameter plot

413-11-29

$\overline{Pt}$ A function of the shape of the size distribution as measured by the standard geometric deviation, σg

Overall Pt

$\overline{Pt} = M_1 \, Pt_1 + M_2 \, Pt_2 = \Sigma \, M_i \, Pt_i$

Where :

M_i = mass of particles having side i.

Where:

d_{RC} is the required cut-diameter

d_{pg} is the geometric-mean particle diameter

(mass-median diamete)

D. Example

Suppose that the size distribution has $d_{pg} = 10\mu$ and $\sigma g = 3.0$ and EPA requires 99% collection efficiency.

Now $\overline{Pt} = 1 - \eta$

$\overline{Pt} = 1 - .99$

$= .01$

from the performance cut-diameter plot for $P_t = .01$, $\sigma g = 3.0$

$$\frac{d_{RC}}{d_{pg}} = .063$$

Since $d_{pg} = 10 \ \mu$ $\quad d_{RC} = .63 \ \mu$

∴ Need to have a scrubber with a cut diameter of .63μ or less to achieve 99% collection efficiency.

E. Scrubber Selection Plot — 413-11-30

1. Gives type of scrubber whose performance will give the required cut diameter
2. Gas phase pressure drop and scrubber power are also given.
3. Cut power relationship given in Figure
    a. Derived from performance test on industrial installations combined with mathematical modeling.
    b. Cut diameter given as a fcn of power input hp/10^3 ft^3/min or gas phase pressure drop (H_2O)
    c. Devised and tested on basis of published data available
    d. Back to example:
    only "unaided" scrubbers capable of giving a .6 μm cut diameter are the gas atomized and fibrous - packed-bed types.
    Require 13" H_2O for gas-atomized scrubber
    e. Power axis is based on 50% efficiency for a fan and motor combination.

F. Limitation of the Technique

In general, the limitations of the techniques for measuring flyash size distributions, undermine the usefulness of the cut-power approach.

V. Contact Power Theory (Another general way of describing scrubber performance) — 413-11-31

A. Introduction — See page 5-44 of Manual

1. Developed by Semrau upon observation of earlier work done by Lapple and Kamak.
2. A completely empirical approach to the design of particulate scrubbers.

413- 11-32
Another empirical approach
Note that this is the most widely used semi-theoretical approach used today
However, do need prior information from similar systems

3. The Fundamental Assumption of Contact Power Theory "When compared at the same power consumption, all scrubbers give substantially the same degree of collection of a given dispersed dust, regardless of the mechanism involved and regardless of whether the pressure drop is obtained by high gas flow rates or high water flow rates."

   413-11-33

   Collection efficiency increases as pressure drop increases — only significant departure is when steam is condensed in the scrubber.

B. Definitions

1. Contacting Power - The power which is dissipated in mixing the dirty gas with the scrubbing liquid. (it does not include mechanical power losses in motors, bearings, etc., nor does it include friction loss in gas flow in the dry state.)

2. Transfer Units

   Remember Penetration?

   Penetration = $1 - \eta$

   (Note: efficiency is usually an exponential function of the process variables for most types of collectors and hence is for correlation purposes an insensitive function in the high efficiency range). (Penetration, is generally preferable under these conditions).

   Still better is the number of transfer units

   $N_t = \ln\left(\frac{1}{1-\eta}\right)$ or $\eta = 1 - e^{-N_t}$

   413-11-34

   413-11-35

   Note analogy to Johnstone eq. Table 1 JAPCA June 1960, 10-3 p.200

3. Total Pressure Loss (P_T)

   (Note P_T is not penetration in this formalism)

P_T = Pressure drop of gas going through the scrubber + Pressure drop of the spray liquid during atomization 413-11-36

$$P_T = \underset{P_G}{\text{Pressure drop of gas going through the scrubber}} + \underset{P_L}{\text{Pressure drop of the spray liquid during atomization}}$$

(a) Gas Pressure Drop 413-11-37

$P_G = 0.1575\Delta P$ = contacting power based upon gas stream energy input (hp/1000 ACFM)

Δ_p = pressure drop across the scrubber (in water)

(b) Power derived from liquid stream 413-11-38

$$P_L = 0.583\, \underset{\substack{\uparrow \\ \text{liquid inlet pressure (psi)}}}{p_L} \left(\frac{Q_L}{Q_G}\right) \begin{matrix} \leftarrow \text{liquid feed rate (gal/min)} \\ \leftarrow \text{gas flow rate (ft}^3\text{/min)} \end{matrix}$$

(c) Therefore, 413-11-39

$$\begin{aligned} P_T &= P_G + P_L \\ &= 0.1575\Delta p + 0.583 p_L \left(\frac{Q_L}{Q_G}\right) \end{aligned}$$

4. Relationship between transfer units and contacting power 413-11-40

$$N_t = \alpha P_T^{\beta}$$

Where α, β are parameters characteristic of the type of particulates being collected.

Relationship independent of type of scrubber.

Relationship cannot predict, can represent what is observed.

Note: $\eta = 1 - e^{-\alpha P_T^{\beta}}$

VI. PILOTING

A. Place of pilot plant data in scrubber design

413.11.41

1. Most large scrubber installations are designed with aide of pilot plant data.
2. Limitations to theoretical approaches for example: Contact Power Theory applies only when energy is confined to one scrubbing area--not good for packed towers.

Refer to:
R.W. McIlvance "When to pilot and when to use theoretical predictions of required venturi pressure drop" APCA paper 77-17.1, presented at 70th Annual Meeting of APCA, Toronto, 1977.

B. Types of pilot plants

1. 1/10 full-scale plants
   example: TVA-Shawnee, 30,000 CFM scrubbers (millions of dollars involved)
2. 2000 CFM plants
   Common size available from many scrubber manufacturers ($20-60,000)
3. 100 CFM plants
   Some skepticism, but have been shown to give accurate predictions
4. 1 CFM miniature scrubber
   New - evidence around to show that it can give accurate predicitons.

VII. LECTURE SUMMARY

Methods for Predicting Venturi Scrubber Pressure Requirements

413-11.42

	DESCRIPTION	EXPENSE (Relative Scale)	TIME (Mos)
Most Reliable	*1/10 size full-scale plants	100-1000	12-24
	*2000 CFM pilot units	30	3-6
	*100 CFM pilot units	5	2-3
	*1 CFM mini-scrubber	1	1
	Empirical curves based on similar processes	0.2	0.2
	Impactor in situ particle sizing	2	1
	Less expensive prediction methods	1	0.5
Least Reliable	Theoretical calculations	0.2	0.2

*All of equal reliability for determining just the pressure requirement.

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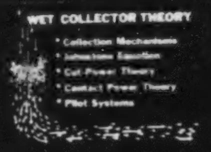
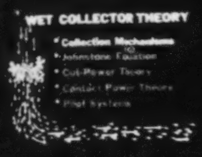
DATE 6/80 ASSIGNMENT 413 L-11 NO 13


WET COLLECTOR THEORY
- Collection Mechanisms
- Johnstone Equation
- Cut-Power Theory
- Contact Power Theory
- Pilot Systems

1

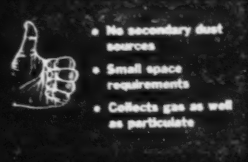

WET COLLECTOR THEORY
- Collection Mechanisms
- Johnstone Equation
- Cut-Power Theory
- Contact Power Theory
- Pilot Systems

2

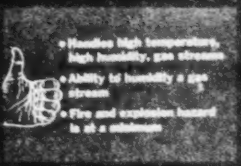
ZONES

1. Contact 2. Separation

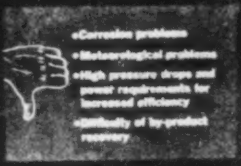
3


- No secondary dust sources
- Small space requirements
- Collects gas as well as particulate

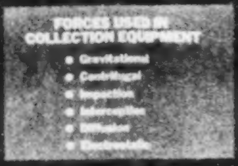
4


- Handles high temperature, high humidity, gas streams
- Ability to humidify a gas stream
- Fire and explosion hazard is at a minimum

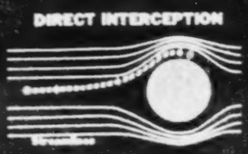
5


- Corrosion problems
- Meteorological problems
- High pressure drops and power requirements for increased efficiency
- Difficulty of by-product recovery

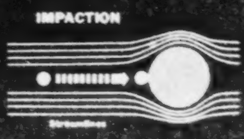
6


FORCES USED IN COLLECTION EQUIPMENT
- Gravitational
- Centrifugal
- Impaction
- Interception
- Diffusion
- Electrostatic

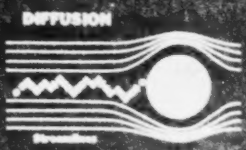
7


DIRECT INTERCEPTION

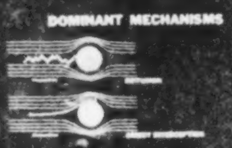
8


IMPACTION

9


DIFFUSION

10


DOMINANT MECHANISMS

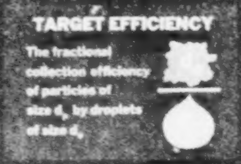
11

Ψ

SEPARATION NUMBER
or
IMPACTION PARAMETER

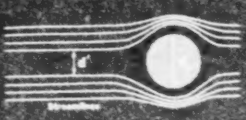
(A dimensionless number characterizing a given collection mechanism)

12


TARGET EFFICIENCY

The fractional collection efficiency of particles of size d_p by droplets of size d_d

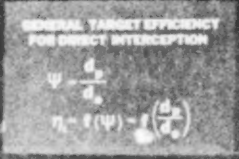
13



14

η_t
area swept clean
collection area

15


GENERAL TARGET EFFICIENCY FOR DIRECT INTERCEPTION

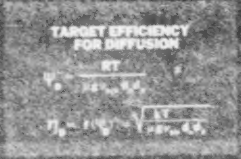
$$\Psi = \frac{d_p}{d_d}$$

$$\eta_t = f(\Psi) = f\left(\frac{d_p}{d_d}\right)$$

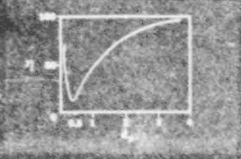
16

IMPACTION PARAMETER FOR INERTIAL IMPACTION

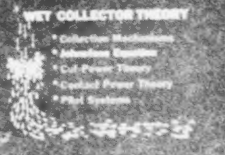
17


TARGET EFFICIENCY FOR DIFFUSION

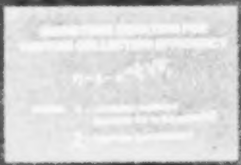
18



19


WET COLLECTOR THEORY
- Collection Mechanisms
- Johnstone Equation
- Cut-Power Theory
- Contact Power Theory
- Pilot Systems

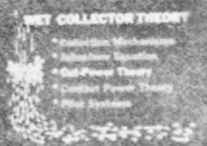
20


21

22

NUKIYAMA – TANASAWA RELATIONSHIP

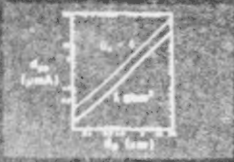
23

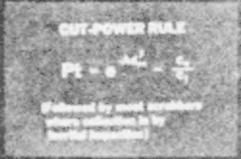

WET COLLECTOR THEORY
- Collection Mechanisms
- Johnstone Equation
- Cut-Power Theory
- Contact Power Theory
- Pilot Systems

24

25

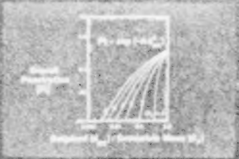
26


27


CUT-POWER RULE

(Followed by most scrubbers where collection is by inertial impaction)

28


29

30

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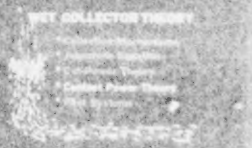
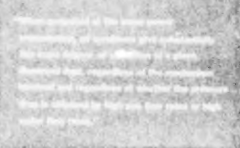
DATE 6/80 ASSIGNMENT 413 L-11 NO.

CONTACT POWER!

31


WET COLLECTOR THEORY
- [illegible]
- [illegible]
- [illegible]
- Contact Power Theory
- [illegible]

32


[illegible]

33

TRANSFER UNITS

$N_t = \ln\left(\frac{1}{1-\eta}\right)$

or

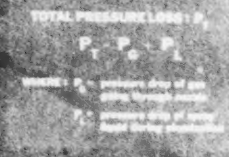
$\eta = 1 - e^{-N_t}$

34

RELATION OF EFFICIENCY TO NUMBER OF TRANSFER UNITS

[illegible]

35


TOTAL PRESSURE LOSS : P_T

$P_T = P_G + P_L$

WHERE: P_G = pressure drop of gas going through nozzle

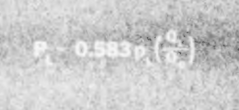
P_L = pressure drop of spray liquid during atomization

36

GAS PRESSURE DROP

$P_G = 0.1575\ \Delta p$

37


$P_L = 0.583\, p_L \left(\frac{Q_L}{Q_G}\right)$

38

$P_T = P_G + P_L$

$0.1575\, \Delta p + 0.583\, p_L \left(\frac{Q_L}{Q_G}\right)$

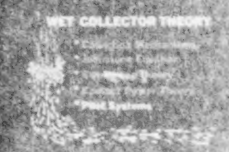
39

RELATIONSHIP BETWEEN TRANSFER UNITS AND CONTACTING POWER

$N_t = \alpha P_T^{\gamma}$

$\eta = 1 - e^{-\alpha P_T^{\gamma}}$

40


WET COLLECTOR THEORY
- [illegible]
- [illegible]
- [illegible]
- [illegible]
- Pilot Systems

41

[illegible]

42

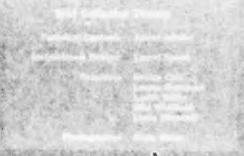
[illegible]

Northrop Services, Inc.

under

EPA Contract No. 68-02-2374

43


Wet Collector Theory

[illegible]

44

LESSON PLAN

AIR POLLUTION TRAINING INSTITUTE

TOPIC: PROBLEM SESSION VII - WET COLLECTOR

COURSE: 413 - Lesson 11a
LESSON TIME: 1 hour
PREPARED BY: J.A. Jahnke
DATE: 3/14/79

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

LESSON GOAL : To review the basic concepts of wet collector theory given in the previous lecture, by direct application of the theory in problem session.

LESSON OBJECTIVES: The student will be able to:

1. Calculate the efficiency of a scrubber by the Contact Power Rule, given the appropriate input parameters.
2. Calculate the penetration associated with a given particle cut diameter and scrubber type, using the cut power rule and also to calculate the pressure drop across the system.
3. Calculate the collection efficiency for a venturi scrubber, using the Johnstone Correlation.

STUDENT PREREQUISITE SKILLS:

Ability to understand basic physical science principles and to perform calculations with logarithms and exponential functions. A basic understanding of the previous lecture on Wet Collector Theory.

LEVEL OF INSTRUCTION: Advanced

INTENDED STUDENT PROFESSIONAL BACKGROUND:

High school math and general science. Understanding of first day's course lecture material.

SUPPORT MATERIALS AND EQUIPMENT:

1. Chalkboard or overhead projector with acetate for working problems.
2. 413 Student Workbook
3. Slide projector

SPECIAL INSTRUCTIONS: Problems 7.1, 7.2, 7.3, and 7.4 deal with wet collector applications. Major emphasis should be placed on the problems dealing with Contact Power Theory.

It is advisable for the instructor to work along with the students in these problems. Get them started, let them work on one step of the problem alone, then after 5 or 10 minutes, explain how the step is to be done. Proceed to the next step of the problem, and so on. Do problem 7.1 in this manner. They should then be able to do problem 7.2 on their own.

Problem 7.3 is difficult for the students to do alone. Although the solution is simple, some of the non-engineering students may find the graphical manipulations unfamiliar. Lead the students on to the solution.

Problem 7.4 should not be done in class, but should be assigned as homework. It will take approximately 1 to 2 hours for the student to solve. Give hints as to how to approach the problem and review the problem in the review session the next morning.

NOTE: The instructor should not view this problem session as "time-off". A good instructor will be present the entire time, assisting the students and leading them in the right direction.

Good students will require less effort, poorer students will demand more effort on the part of the instructor.

REFERENCES:

1. 413 Student Manual
2. Calvert, S., "How to Choose a Particulate Scrubber," Chemical Engineering, August 29, 1977, pp. 54-68.
3. Semrau, K. T., "Practical Process Design of Particulate Scrubbers", Chemical Engineering, September 26, 1977, pp. 87-91 (and references therein).
4. McIlvaine, R. W., "When to Pilot and When to Use Theoretical Predictions of Required Venturi Pressure Drop." APCA paper #77-17.1 70th Annual Meeting of APCA, Toronto, Ontario, June 20-24, 1977.
5. Perry, R. H. and Chilton, C. H., Chemical Engineer's Handbook Fifth Edition, 1973, McGraw-Hill, N.Y., pp. 20-94 - 20-97.
6. Kashdan, E. R. and Ranade, M. B., "Design Guidelines for an Optimum Scrubber System", EPA-600/7-79-018, Jan. 1979.

I. Introduction

A. Application of Theory

1. Note role of theoretical calculations in wet collector design.

2. Note that a knowledgeable environmental engineer should be familiar with the calculations and terminology used in the problems.

B. Tell how you will conduct the problem session.

II. Problem 7.1 - Contact Power Theory Application
page 25 of 413 Student Workbook

A vendor proposes to use a spray tower on a lime kiln operation to reduce the discharge of solids to the atmosphere. The inlet loading of the gas stream from the kiln is 5.0 grains/ft^3 and is to be reduced to 0.05 in order to meet state regulations. The vendor's design calls for a water pressure drop of 80 psi and a pressure drop across the tower of 5.0 in. H_2O. The gas flow rate is 10,000 ACFM, and a water rate of 50 gal/min is proposed. Assume the contact power theory to apply.

This problem and the solution are given on pages 5-49 to 5-53 of the Course 413 Manual. The students probably will not realize this - if some do, ask them to solve the problem with the book closed.

1. **Will the spray tower meet regulations?**
2. **What total pressure loss is required to meet regulations?**
3. **Propose a set of operating conditions that will meet the standard. The maximum gas and water pressure drop across the unit are 15 in. H_2O and 100 psi, respectively.**
4. **What conclusions can be drawn concerning the use of a spray tower for this application.**

Solution

For part 1, the collection efficiency is calculated from Equation 5.2.8.

$$N_t = \ln [1/(1 - \eta)]$$

Also

$$N_t = \alpha P_T^{\beta}$$

P_T is calculated as follows:

$$\begin{aligned}
P_T &= P_G + P_L \\
P_G &= 0.157\ \Delta P \\
&= 0.157\ (5) = 0.785 \\
P_L &= 0.583 p_L\ (Q_L/Q_G) \\
&= 0.583\ (80)\ (50/10{,}000) = 0.233 \\
P_T &= 1.018\ \text{hp}/1{,}000\ \text{ACFM}
\end{aligned}$$

For a lime kiln dust and/or fume, $\alpha = 1.47$ and $\beta = 1.05$ (Table 5.2.1). Thus,

$$N_t = 1.47\ (1.018)^{1.05} = 1.50$$

Substitution into Equation 5.2.8

$$\begin{aligned}
1.5 &= \ln [1/(1 - \eta)] \\
\eta &= 77.7\%
\end{aligned}$$

Since the regulations require (5.0 - 00.5)/5.0 = 99%, the spray tower will not meet the regulations.

For part 2, calculate P_T for $\eta = 0.99$.

$$\begin{aligned}
N_t &= \ln [1/(1 - 0.99)] = 4.605 \\
4.605 &= 1.47\ (P_T)^{1.05} \\
P_T &= 2.96\ \text{hp}/1{,}000\ \text{ACFM}
\end{aligned}$$

For part 3, assume the maximum gas and water pressure drop across the unit to be 15 in. H_2O and 100 psi, respectively. Calculate P_G and P_L.

$P_G = 2.36$

$P_L = 0.60$

Calculate (Q_L/Q_G) in gallons per 1,000 ACF

$$(Q_L/Q_G) = P_L/0.583\ p_L = 0.6\ (1{,}000)/0.583\ (100)$$
$$= 10.3\ \text{gal}/1{,}000\ \text{ACFM}$$

Determine new water flow rate.

(10.3 gal/1,000 ACFM) (10,000 ACFM) = 103 gal/min

For part 4, the unit has limited, at best applicability for high collection efficiency operations.

III. Problem 7.2 Contact Power Theory Application
page 26 of 413 Student Workbook

The installation of a venturi scrubber is proposed to reduce the discharge of particulates from an open-hearth steel furnace operation. Preliminary design information suggests a water and gas pressure drop across the scrubber of 5.0 psi and 36 in. H_2O, respectively. A liquid-to-gas ratio of 6.0 gal/min/1,000 ACFM is usually employed in this application. Estimate the collection efficiency of the proposed venturi scrubber. Assume contact power theory to apply.

This problem and solution is also given in the 413 Course Manual. Depending on the time situation, have the students work the problem alone, or assign it as homework.

Due to the low water pressure drop, it can be assumed that

$$P_G >>> P_L ; P_T \cong P_G$$

with

$P_G = 0.157\ (\Delta P)$

Solving for P_G gives

$$\begin{aligned} P_G &= 0.157\ (36) \\ &= 5.65\ \text{hp}/1{,}000\ \text{ACFM} \end{aligned}$$

The number of transfer units is calculated from

$$N_t = \alpha P_T^{\beta}$$

where α and β are 1.26 and 0.57, respectively, for this industry (Table 5.2.1). Thus,

$$\begin{aligned} N_t &= 1.26\ (5.65)^{0.57} \\ &= 3.38 \end{aligned}$$

The collection efficiency can now be calculated.

$$\begin{aligned} N_t &= \ln\ [1/(1 - \eta)] \\ \eta &= 0.966 = 96.6\% \end{aligned}$$

IV. Problem 7.3 Cut Power Rule
page 27 of the 413 Student Workbook

What would be the pressure drop required on a Venturi scrubber to achieve an overall collection efficiency of 99.3% for particulate matter having a mass-median diameter of 5 μmA with particle size deviation, σ_g, of 2.0 μm?

P.S. VII-1

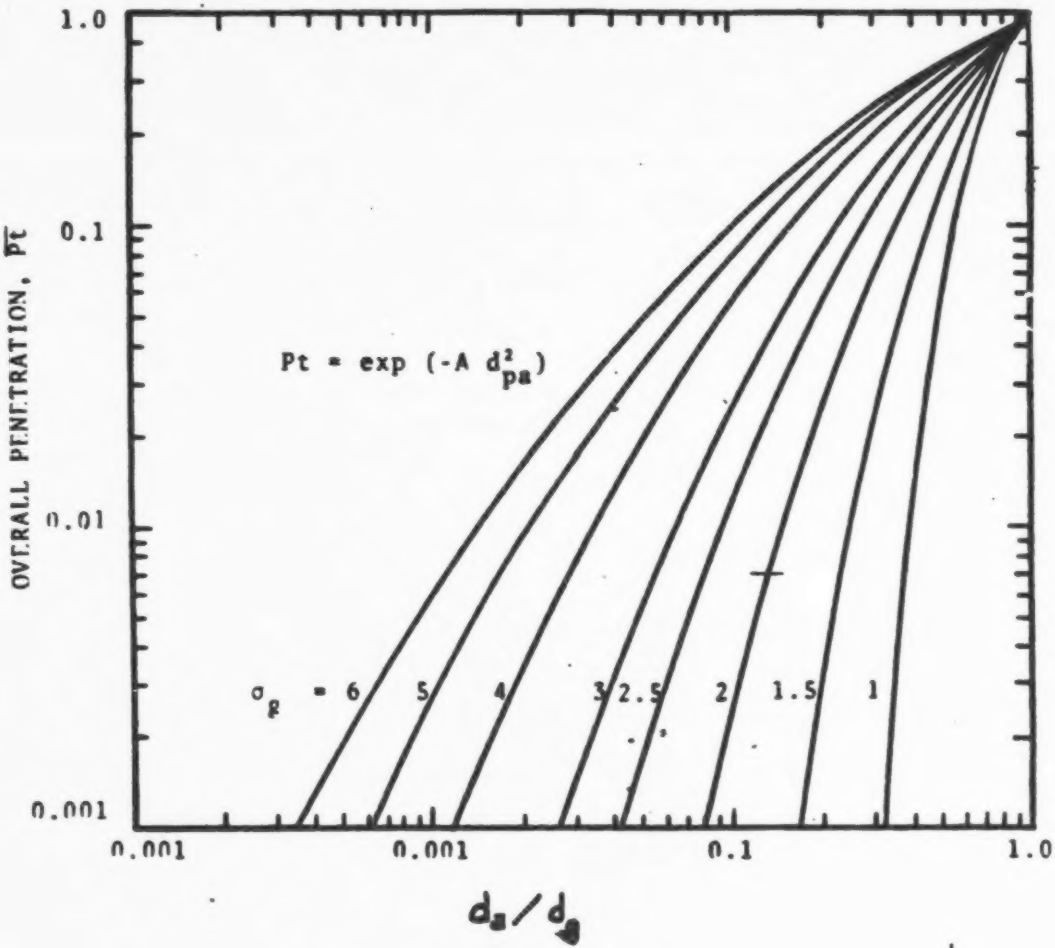


Figure 1

SOLUTION:

Required efficiency $\eta = .993$

$\therefore$ penetration

$\overline{Pt} = 1 - \eta$

$\overline{Pt} = 0.007$

From Figure 1., with $\overline{Pt} = .007$ and $\sigma_g = 2.0$ µm

Find $\frac{da}{dg} = 0.13 = \frac{\text{aerodynamic cut diameter required}}{\text{particle mass mean diameter}}$

If you have not already done so in the lecture, it may be necessary to review the definitions of cut diameter and mass mean diameter.

$da = dg\ (0.13)$

dg is given as 5 µm

$\therefore da = 5 \times .13$

$= .65$ µm

P.S. VII
2

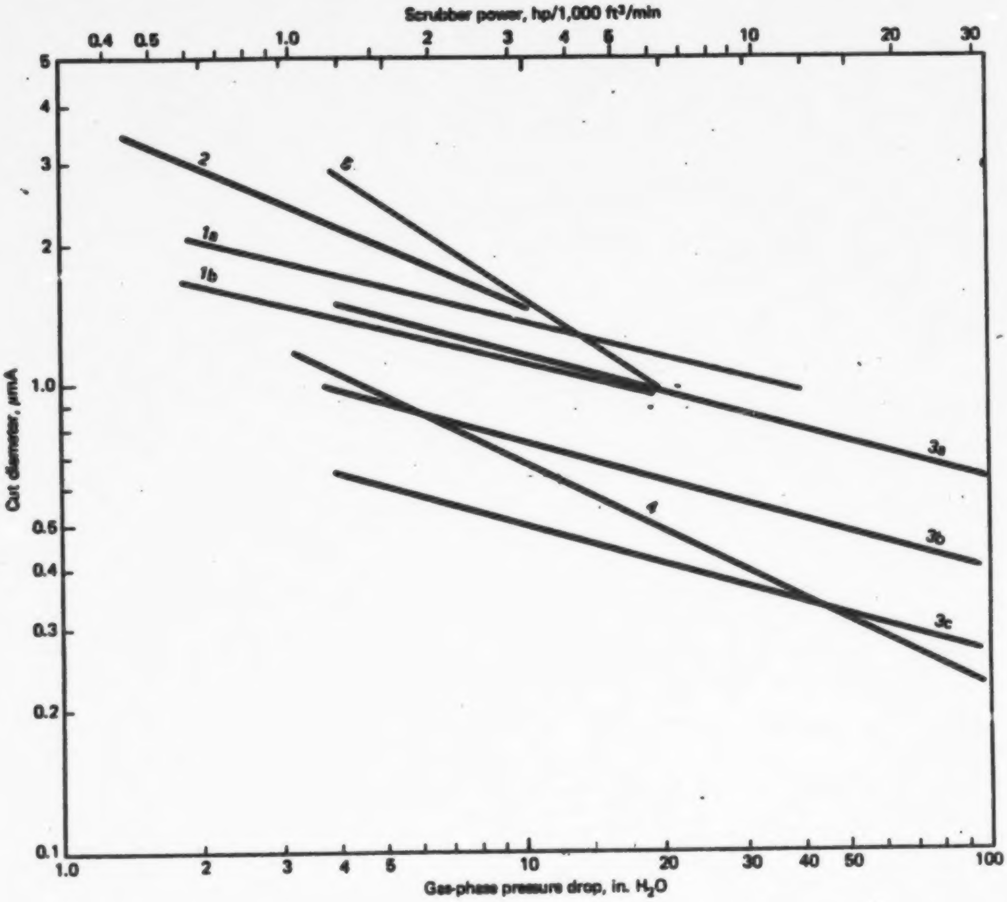


Figure 2

From Figure 2 find the pressure drop for a venturi (Curve #4)

$\Delta p \approx 12'' \; H_2O$

After you have completed problem Note the

empirical nature of the theory to the student. Also note the similarities to Contact Power Theory

7.4 Johnstone Equation for Venturi Scrubbers

page 29 of the 413 Student Workbook

A fly ash laden gas stream is to be cleaned by a venturi scrubber using a liquid to gas ratio of 8.5 gal/1000 ft^3. The efficiency can be calculated from

$$\eta_i = 1 - \exp\left(-K\frac{Q_L}{Q_G}\sqrt{\psi_i}\right)$$

Where η_i is the fractional efficiency of collection of particles of size d_{pi}. The fly ash has a particle density of 0.7 gm/cm^3, and k= 200 ft^3/gal. Use a throat velocity of 272 ft/sec, a liquid to gas ratio of 8.5 gal/1000 ft^3, and a gas viscosity of 1.5 x 10^{-5} lb/ft sec. The particle size distribution is:

d_{pi} (microns)	% by Weight
< 0.10	0.01
0.1 - 0.5	0.21
0.6 - 1.0	0.78
1.1 - 5.0	13.0
6.0 - 10.0	16.0
11.0 - 15.0	12.0
16.0 - 20.0	8.0
> 20.0	50.0

Make use of the Nukiyama and Tanasawa relationship.

NOTE:
This is a classical problem. Although the method may not be used extensively in the industry, it gives an estimate for Venturi's. The method points out a number of important factors that should be considered in control equipment design. Besides it's good for the student's soul. Assign as homework don't attempt to solve it in class.

Review the following morning.

SOLUTION to Problem 7.4

a. Mean droplet diameter

The Nukiyama-Tanasawa correlation can be used for an air-water system:

$$d_e = \frac{16400}{u} + 1.45 \left(\frac{Q_L}{Q_G}\right)^{1.5}$$

$$= \frac{16400}{272\ \text{ft/sec}} + 1.45\ (8.5\ \text{gal}/1000\ \text{ft}^3)^{1.5}$$

$$d_e = 96.23\ \text{microns}$$

b. Inertial impaction number Ψ

$$\Psi_i = \frac{d_p^2\ \rho_p\ u}{8\ \mu d_e}$$

$$= \frac{d_p^{\ 2}(0.7 \times 62.4\ \text{lb/ft}^3)(272\ \text{ft/sec})}{8\ (1.5 \times 10^{-5}\ \text{lb/ft sec})(96.23\mu)(25400\ \mu/\text{inch})(12\ \text{inch/ft})}$$

$$\Psi_i = 1.500\ d_p^{\ 2}$$

c. Individual efficiencies, η_i

$$\eta_i = 1\text{-exp}\ \left[-K\frac{Q_L}{Q_G}\sqrt{\Psi_i}\right]$$

$$= 1\text{-exp}\ \left[-(0.2 \times 1000\ \frac{\text{ft}^3}{\text{gal}})\ (8.5\ \frac{\text{gal}}{1000\ \text{ft}^3}\ \sqrt{1.5\ d_p^{\ 2}}\right]$$

$$\eta_i = 1\text{-exp}\ [-2.082\ d_p]$$

d. Overall Efficiency

d_p (microns)	η_i	X_i (%)	$\eta_i X_i$
0.05	0.0989	0.01	9.886×10^{-6}
0.30	0.4645	0.21	9.755×10^{-4}
0.80	0.8109	0.78	6.325×10^{-3}
3.0	0.9981	13.0	1.298×10^{-1}
8.0	1.0000	16.0	0.16
13.0	1.0000	12.0	0.12
18.0	1.0000	8.0	0.08
80.0	1.0000	50.0	0.50
		100.0	$\eta_T = 0.9971$

LESSON PLAN

AIR POLLUTION TRAINING INSTITUTE

TOPIC: WET COLLECTOR DESIGN

COURSE: 413 - Lesson 12
LESSON TIME: 1 hour
PREPARED BY: DATE:
J. A. Jahnke 2/19/79

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

LESSON GOAL: To present the basic types of commercially marketed particulate wet scrubbers and to describe their basic modes of operation along with the advantages and disadvantages associated with each type.

LESSON OBJECTIVES: The student will be able to:

* Group the different types of wet scrubbers according to their mechanism of power input.
* Describe the operation of at least 5 of the following types of scrubbers using appropriate diagrams.
  - Plate
  - Gas-atomized spray
  - Centrifugal
  - Baffle
  - Self-induced spray
  - Moving bed
  - Performed spray
  - Mechanically aided
  - Packed
* Discuss the performance characteristics of at least 4 different types of wet collectors, including pressure drop, liquid to gas ratio and problems associated with the design.
* List at least 5 source categories where wet collectors could be suitable applied to control particulate emissions.
* Describe some typical example installations.
* Discuss some typical operation and maintenance problems associated with wet collectors.

SUPPORT MATERIALS AND EQUIPMENT:

1. slide projector
2. chalkboard
3. 413 Student Manual

SPECIAL INSTRUCTIONS:

This lecture is rather descriptive and can get somewhat tedious to the student. It would be helpful for the instructor to use slides from his personal collection, if available, of wet scrubber installations, and to "punch-up" the lecture with some personal anecdotes.

REFERENCES:

1. 413 Student Manual
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4. Strauss, W., Industrial Gas Cleaning (2nd edition) Pergamon Press, Oxford, Chapter 9, pp. 367-407.
5. Best Reference — Bethea, R. M., Air Pollution Control Technology, Van Nostrand Reinhold Co., N.Y., 1978.
6. Perry, R. H. and Chilton, E. H., Chemical Engineers Handbook, Fifth Edition, 1973, McGraw Hill, N.Y. pp. 20-94 -- 20-97
7. McIlvaine, R.W., "Scrubber Operation and Maintenance Survey", Paper 79-49.5 presented at 72nd Annual Meeting of Air Pollution Control Association, Cincinnati , OH, June 24-29, 1979.

AUDIO-VISUAL MATERIALS FOR LESSON 12

Lesson 12	Wet Collector Design
413-12-1	Wet Scrubbers for Particulate Control
413-12-2	Types of Scrubbers
413-12-3	Particulate Scrubber Descriptions
413-12-4	Scrubbers Using Energy from Gas Stream
413-12-5	Sieve Plate Scrubber
413-12-6	Impingement Scrubber
413-12-7	Detail of a Baffle Plate
413-12-8	Detail of a Bubble Cap Plate
413-12-9	Venturi Scrubber (Peabody)
413-12-10	Swirl Venturi Scrubber
413-12-11	Spray Venturi Scrubber
413-12-12	Venturi Scrubber (Flexi-Venturi)
413-12-13	Venturi-Rod Scrubber
413-12-14	Swirl Orifice Scrubber
413-12-15	Detail of Orifice Action
413-12-16	Impingement Scrubber (External View)
413-12-17	Scrubbers Using Energy from Liquid Stream
413-12-18	Simple Spray Chamber
413-12-19	Ejector Scrubber

413-12-20	Scrubbers Using Energy from Liquid and Gas Streams
413-12-21	Moving Bed Scrubber
413-12-22	Baffle Spray Chamber
413-12-23	Cyclonic Spray Scrubber
413-12-24	Irrigated Cyclone
413-12-25	Scrubbers Using Energy from Mechanically Driven Rotor
413-12-26	Mechanical Scrubber
413-12-27	Vertical Spray Rotor
413-12-28	Scrubbers Using Other Configurations
413-12-29	Packed Tower
413-12-30	Common Tower Packing Materials
413-12-31	Packing Materials
413-12-32	Tellerite Packing
413-12-33	Cross Flow Scrubber
413-12-34	Solid Cone Spray Nozzle/Pin Jet Impingement Spray Nozzle
413-12-35	Fiber Bed Scrubber
413-12-36	Charged Wet Scrubber
413-12-37	Operation/Maintenance for Wet Scrubbers

AIR POLLUTION TRAINING INSTITUTE

CONTENT OUTLINE

Course: 413 - Lesson 12
Lecture Title: WET COLLECTOR DESIGN

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

NOTES

I. Introduction

Slide 413-12 -1

- A. Many types of designs -- will give major types here
- B. Because of implications of contact power theory,
  i.e. that efficiency is determined by power dissipation -- independent of scrubber geometry
  efficiency is independent of scrubber geometry and the way the power is applied to the gas-liquid contacting.
- C. Manufacturers and users have turned to a few relatively simple designs primarily:
  - Venturis
  - Orifice Scrubbers

II. Characterization of Scrubber Types

- A. Characterize in terms of how energy for gas-liquid contacting is supplied

  413-12-2

  1. From the energy of the gas stream
  2. From the energy of the liquid stream
  3. From a mechanically driven rotor
  4. Combination devices
- B. Underlying mechanisms are essentially the same within each grouping. "High energy" scrubbers used to collect fine particulates are not fundamentally different from other scrubbers, but incorporate mechanical arrangements that aide power input
- C. Types of scrubbers will talk about:
  1. Energy from gas stream (gas-phase contacting power)
     - (a) Plate Scrubbers -- sieve
       - bubble cap
       - impingement
     - (b) Gas-atomized spray - venturi
       - orifice
       - rod Bank

Write on chalk board

NOTE: can also separate in terms of energy.

Low energy
< 5" pressure drop

(c) Self-induced spray (Impingement and entrainment)	High energy <15" Example - low-spray towers
(d) Baffle	Medium-centrifugal atomized-impingement packed bed
2. Energy from the liquid stream (liquid-phase contacting power)	
(a) Preformed spray - spray tower cocurrent,	High - venturi
(b) countercurrent	
(b) centrifugal - cyclone spray	
(c) ejector venturi	
3. Energy from mechanically driven rotor (mechanical contacting power)	
(a) Motor driven devices (wet dynamic)	
(b) Disintegration scrubber	
4. Miscellaneous scrubbers	
(a) Wet film collectors - massive packed fibrous packed	
(b) Combination devices	
5. Have about 20 types of scrubber designs that want to talk about. For each, will describe	413-12-3
(a) How it works	
(b) Gas velocity	
(c) Pressure drop	
(d) Efficiency - cut diameter	
(e) Liquid to gas ratio	
(f) Source categories which scrubber design is most commonly used.	
III. Scrubbers (Gas - Phase Contacting)	413-12-4
A. Plate Scrubbers	
1. Sieve Plate	413-12-5
(a) How it works: vertical tower with one or more plates (trays) mounted transversly inside -- liquid flows over plates gas contacts liquid through perforations - 600-3000 holes/ft^2 -- holes not aligned.	

(b) Gas velocity range
(c) Pressure drop
(d) Efficiency - cut diameter - $\sim$1.0 μm for 1/8" diameter holes
(e) Liquid to gas ratio
(f) Source category usage
Drying processes, nonferrous metals

2. Impingement Plate — 413-12-6
(a) How it works - impingement baffles placed above each perforation on a sieve plate. Bubble caps and other configurations. Some have moveable caps for high turn-down ratios. — 413-12-7, 413-12-8
(b) Gas velocity range - 15-20 ft/sec through each orifice is common.
(c) Pressure drop - 1 to 8" H_2O, 1.5" H_2O common
(d) Efficiency - cut diameter - 2→3 μm cut diameter, 90→98% efficiency for 1 μm particle /plate.
(e) Liquid to gas ratio - 3 → 15 gal $H_2O/1000\ ft^3$ gas
5 psig water pressure common, some can go to 50,000 ACFM
(f) Usage - drying processes, cupolas, kilns, fertilizer

B. Gas atomized spray scrubbers
1. Venturi — 413-12-9
(a) How it works - contraction to increase gas velocity introduce liquid at throat or along the walls of the inlet to the throat. Gas shears off water from nozzles or walls and atomizes. — 413-12-10, 413-12-11
(b) Gas velocity - 12,000 24000 ft/min through the throat
(c) pressure drop - 6 →20 →60 →100"
(25-30" is common)
(d) Efficiency - cut diameter — See pp 5-32 & 5-33 of Manual for efficiency curves
100% for 1→ 2 μm at 10" H_2O
99% for.3 - .4 at 60" H_2O
Cut diameter .05 - .1" at 60 to 100" H_2O
(e) Liquid to gas ratio - 3 - 10 gal/1000 ft^3
Droplet sizes usually about 10 μm in diameter

TABLE 1

TYPICAL PERFORMANCE DATA FOR VENTURI SCRUBBER*

Source of Gas	Contaminants	Approximate Size Range (Microns)	Loading (Grains/ cf)		Average Removal Efficiency (%)
			Inlet	Exit	
IRON & STEEL INDUSTRY					
Gray Iron Cupola	Iron, Coke, Silica Dust	1-10	1-7	.05-.15	95
Oxygen Steel Converter	Iron Oxide	5-2	8-10	05-08	98.5
Steel Open Hearth Furnace (Scrap)	Iron & Zinc Oxide	.08-1	.5-1.5	03-.06	35
Steel Open Hearth Furnace (Oxygen Lanced)	Iron Oxide	5-2	1-6	.01-.07	99
Blast Furnace (Iron)	Iron Ore & Coke Dust	.5-20	3-24	.008-.05	99
Electric Furnace	Ferro-Manganese Fume	.1-1	10-12	.04-.08	99
Electric Furnace	Ferro-Silicon Dust	.1-1	1-5	.1-.3	92
Rotary Kiln—Iron Reduction	Iron, Carbon	.5-50	3-10	.1-.3	99
Crushing & Screening	Taconite Iron Ore Dust	.5-100	5-25	.005-.01	99.9
CHEMICAL INDUSTRY					
Acid—Humidified SO_3	H_2SO_4 Mist				
(a) Scrub with Water		—	303*	1.7*	99.4
(b) Scrub with 40% Acid		—	406*	2.8*	99.3
Acid Concentrator	H_2SO_4 Mist	—	136*	3.3*	97.5
Copperas Roasting Kiln	H_2SO_4 Mist	—	198*	2.0*	99
Chlorosulfonic Acid Plant	H_2SO_4 Mist	—	756*	7.8*	98.9
Dry Ice Plant	Amine Fog	—	25*	2.0*	90+
Wood Distillation Plant	Tar & Acetic Acid	—	1080*	58.0*	95
$TiCl_4$ Plant, TiO_2 Dryer	TiO_2-HCl Fumes	.5-1	1-5	.05-.1	95
Spray Dryers	Detergents, Fume & Odor	—	—	—	95
Flash Dryer	Furfural Dust	.1-1	1-1.5	.05-.08	95+
Phosphoric Acid Plant	H_3PO_4 Mist	—	192*	3.8*	98+
NON-FERROUS METALS INDUSTRY					
Blast Furnace (Sec. Lead)	Lead Compounds	.1-1	2-6	.05-.15	99
Reverberatory Lead Furnace	Lead & Tin Compounds	.1-.8	1-2	.12	91
Ajax Furnace—Aluminum Alloy	Aluminum Chloride	.1-.9	3-5	.02-.05	95
Zinc Sintering	Zinc & Lead Oxide Dusts	.1-1	1-5	.05-.1	98
Reverberatory Brass Furnace	Zinc Oxide Fume	.05-.5	1-8	.1-.5	95
MINERAL PRODUCTS INDUSTRY					
Lime Kiln	Lime Dust	1-50	5-10	.05-.15	99+
Lime Kiln	Soda Fume	.3-1	2-5	.01-.05	99
Asphalt Stone Dryer	Limestone & Rock Dust	1-50	5-15	.05-.15	98+
Cement Kiln	Cement Dust	.5-55	1-2	.05-.1	97+
PETROLEUM INDUSTRY					
Catalytic Reformer	Catalyst Dust	.5-50	.09	.005	95+
Acid Concentrator	H_2SO_4 Mist	—	136*	3.3*	97.5
TCC Catalyst Regenerator	Oil Fumes	—	756*	8.0*	98+
FERTILIZER INDUSTRY					
Fertilizer Dryer	Ammonium Chloride Fumes	.05-1	.1-.5	.05	85+
Superphosphate Den & Mixer	Fluorine Compounds	—	309*	5.5*	98+
PULP & PAPER INDUSTRY					
Lime Kiln	Lime Dust	.1-50	5-10	.05-.15	99+
Lime Kiln	Soda Fume	.1-2	2-5	.01-.05	99
Black Liquor Recovery Boiler	Salt Cake	—	4-6	.4-.6	90
MISCELLANEOUS					
Pickling Tanks	HCl Fumes	—	25*	2.3*	90+
Boiler Flue Gas	Fly Ash	.1-3	1-2	.05-.08	98
Sodium Disposal Incinerator	Sodium Oxide Fumes	.3-.1	.5-1	.02	98

* Milligrams per cubic ft

Note: The efficiencies shown above are average values for a particular plant or group of installations operating under a specific set of conditions.

*Chemico Gas Scrubbers for Industry, Bulletin M-104, Chemical Construction Corp., 525 West 43 St., NY, NY.

(f) Source category usuage - see table attached in general - pulverized coal, abrasives, rotary kilns, foundries, flue gas, cupola gas, fertilizers, lime kilns, etc.

pick out examples from table

2. Orifice (variable float venturis) — 413-12-12

Can adjust pressure drop and scrubber efficiency

3. Rod bank

Parallel rods - can rotate - spray water on rods - cocurrent with gas flow -- a series of parallel venturi throats Δp = 2" → 150" H_2O, 90 → 600,000 ACFM units. L/G = 2 → 15 gal/1000 ft^3 — 413-12-13

C. Self-Induced Spray - Impingement and Entrainment - Also called orifice wet scrubber (in manual) — 413-12-14

1. How it works: Gas impinges on and skims over liquid in turn, atomizes the liquid — 413-12-15
2. Gas velocity - 50 ft/sec gives droplets 300 to 400 μm in size,can go to 600 ft/sec for submicron size particles. — 413-12-16
3. Pressure drop - 3 → 10" (drop size - 60 μm)
4. Efficiency - cut diameter - .8 to 1 μm at 3 → 6" H_2O, can handle high dust concentrations
5. Liquid to gas ratio - get water recirculation, so have around 1-3 gal/1000 ft^3
6. Source Category Usage

   calcining operations, combustion sources

   coal mining, ore mining, explosive dusts, incineration.

IV. Scrubber (Liquid-Phase Contacting) or Preformed Spray Scrubbers — 413-12-17

A. Spray towers

1. How it works: — 413-12-18

   Most common low-energy scrubber. Collects particles on liquid droplets which are preformed.

   Properties of droplets are determined by:

   - configuration of the nozzle
   - liquid atomized
   - pressure to the nozzle

In vertical towers, the terminal settling velocity corresponds to the relative velocity between particles and the gas.

In practice -- verticle gas velocity 2-5 fps for good collection, need high V_{rel}.
small size drops

conditions, however, are incompatible:
small drops → low free-falling velocity

∴ have an optimum droplet size for a given particle size for maximum collection efficiency

Maximum efficiency for particles <5μ is at water droplet size ∿ 80μ

2. Gas velocity - 1 → 5 ft/sec
3. Pressure drop - .5 → 2" H_2O
4. Efficiency - low efficiency 70% > 5 μm
5. Liquid to gas ratio - .5 → 8 gal/1000 ft^3
   can handle large gas volumes - often used as a pre-cooler
6. Usage - dust cleaning, electroplating, phosphate fertilizer, kraft paper, smoke abatement, pre-cooler, blast furnace gas.

Different designs
- co-current
- countercurrent
- cross-flow

B. Ejector Venturi (jet venturi)
1. How it works: Water pumped through a nozzle at high velocity. Dirty gas accelerated by the action of the jet. Causes considerable turbulence and a lowering of the pressure - development of a mist.
2. Gas velocity - 15-50 ft/sec
3. Pressure Drop - 1-3" H_2O
4. Efficiency - cut diameter ∿ .8 μm
5. Liquid to gas ratio - 50-100 gal/1000 ft^3
6. Usage - Fertilizer manufacture, odor control, smoke control.

Note: could also use heated water in jet. page 5-28 of Manual

413-12-19

V. Scrubbers (gas phase - liquid phase contacting)

1. Moving bed scrubbers - (also turbulent contact absorbers - TCA)
   a. How it works - have zone of movable packing where gas and liquid can mix packing may be 1½" diameter polyethylene or polypropylene spheres may use several stages.
   b. Gas velocity
   c. Pressure drop - $3 \rightarrow 5''\ H_2O$
   d. Efficiency - 99% for particles down to 2 μm
   e. Liquid to gas ratio
   f. Source category usage - Kraft paper, basic oxygen steel, fertilizer, aluminum ore reduction aluminum refineries, asphalt manufacturing.

413-12-20
NOTE: may use sprays so have combination of processes both gas phase and liquid phase contacting

413-12-21

Energy of removal can come from both gas phase and liquid phase

2. Baffle Scrubber and Secondary flow scrubbers
   a. How it works -- change direction of flow by solid surfaces, louvres, zig-zags, etc. may use sprays or wetted walls and baffles to remove particulates.
   b. Gas velocity
   c. Pressure drop - low
   d. Efficiency - cut diameter - cut diameter 5-10 μm, low for fine particles
   e. Liquid to gas ratio
   f. Source category Usage
      Coke quenching, Kraft paper manufacture, plating, useful as precleaners and entrainment separators.

413-12-22

3. Centrifugal Collectors
   a. How it works: Usually cylindrical in shape impart a spinning motion to the gas passing through them. Spinning comes from tangential introduction direction of gas stream against stationary swirl vanes. Particle collection operates by centrifugal deposition caused by the rotating gas stream

cross between a spray chamber and a cyclo

413-12-23

413-12-24

b. Gas velocity - gas velcities 200 → 500 ft/sec

c. Pressure drop - 1.5 to 3" H_2O are typical

d. Efficiency - cut-diamter - cut diameter generally 2 to 3 μm. 90% efficient for particles <5 μm

e. Liquid to gas ratio - 2 to 10 gal/1000 ft^3 capacity ∿ 50,000 ACFM/unit

f. Source category Useage
Spray dryers, calciners, crushers, classifiers, fluid bed processors, kraft papers, fly ash.

Polycon cyclone spray
Irrigated cyclone
cyclonic - internal spray - outer wall

Multiwash scrubber (vanes)

centripetal vortex contactor
(p. 5-34 of manual)

VI. Scrubbers (Mechanical Contacting Power) 413-12-25

A. Incorporate a motor-driven device between the inlet and the outlet of the scrubber body 413-12-26

Example - Disintegrator Scrubber 413-12-27

1. How it works: uses a submerged, motor-driven impeller to atomize liquid into small drops. Drops spin off the impeller across the gas stream, collecting particles on the way.
2. Gas Velocity
3. Pressure Drop - <1"
4. Efficiency - ∿ 1 μm at 90% efficiency
5. Liquid to gas ratio
6. Usage - blast furnace gas

Another example: Submerged Rotor (page 5-39 of Manual) Droplets mechanically induced 4 - 5 gal/1000 ft^3 - low liquid levels small in size, but get abrasion and errosion Usage - iron foundry, cupolas chemical fume control, paint spray.

VII. Miscellaneous Scrubbers 413-12-28

Note: Bethea has good summary p. 281

- A. Wet Film Collectors
  - 1. Massive Packed
    - a. How it works: get centrifugal deposition through flow channels - have several designs: co-current, countercurrent, crossflow. 413-12-29 413-12-30
    - b. Gas velocity 413-12-31 413-12-32
    - c. Pressure drop - ∿ 4" H_2O(or .5" H_2O per foot of packing) may be 2-10" overall 413-12-33
    - d. Efficiency - cut diameter of 1.5 μm with 1" H_2O Berl saddles - the smaller the packing, the higher the efficiency. 413-12-34
    - e. Liquid to gas ratio - 2-5 gal/1000 ft^3 gas rates ∿ 35,000 CFM or less
    - f. Usage - More often for gases
  - 2. Fibrous Packed 413-12-35
    - a. How it works: Plastic, glass, and steel fibers 97-99% void space - impaction is the dominant mechanism - efficiency increases as fiber gets smaller and gas velocity increases.
    - b. Gas velocity
    - c. Pressure drop ∿ 4" H_2O
    - d. Efficiency - cut diameter 1-2 μm for .01" diameter fibers
    - e. Usage -
  - 3. Flooded Bed

    Operated co-current - dirty gas and scrubber liquid enter from bottom - sprays flood bottom of packed layer. Upward gas velocity keeps bed expanded to prevent plugging. Cut diameter of 2 - 3 μm with pressure drops as high as 10-15" H_2O

B. Combination Categories

1. Use a combination of scrubber types. Maintenance problems are the same as those of the individual types which they are made up of.

2. Examples
   a. Foam Scrubbers
      Use surfactants to encapsulate the airstream into bubbles.
   b. Steam Assisted Scrubbers
      Steam or high-temperature water is driven from nozzle at high speed
   c. Charged Wet Scrubbers
      combine advantages of scrubbers and precipitators

413-12-36

   d. Condensation Scrubbers
      Condense droplets from the gas stream

VIII. Operation and Maintenance for Scrubbers

413-12-37

A. The scrubber situation is considerably more complex than the fabric filter or precipitator situation. This is because of the wide variety of scrubber designs Maintenance characteristics are considerably different for each type. Therefore, it is not meaningful to generalize on scrubber maintenance problems but only to draw conclusions about the maintenance characteristics of a specific type.

Mechanically-aided scrubbers are likely to have high maintenance because of the more complex design and moving parts. Venturi scrubbers are also vulnerable because of the high velocity in the venturi throat. Spray towers are among the most maintenance-free scrubber designs and for this reason are finding increasing use in flue gas desulfurization.

B. Specific Operations and Maintenance problems for gas-atomized spray scrubbers.

Among the most widely used of the gas atomized types is the venturi scrubber.

1. The velocities through venturi throats may be as high as 40,000 fpm. At these velocities, the wear rates are quite high in the throat section unless abrasion resistant construction materials are used.

2. Throats are often lined with silicon carbide brick to extend throat life. Replaceable wear liners are another feature that prevents deterioration of the throat section. High wear occurs in areas downstream of the acceleration zone.

3. The distance from the throat through which high wear potential exists is related to the throat diameter. In larger venturis, erosion potential exists to a distance farther downstream.

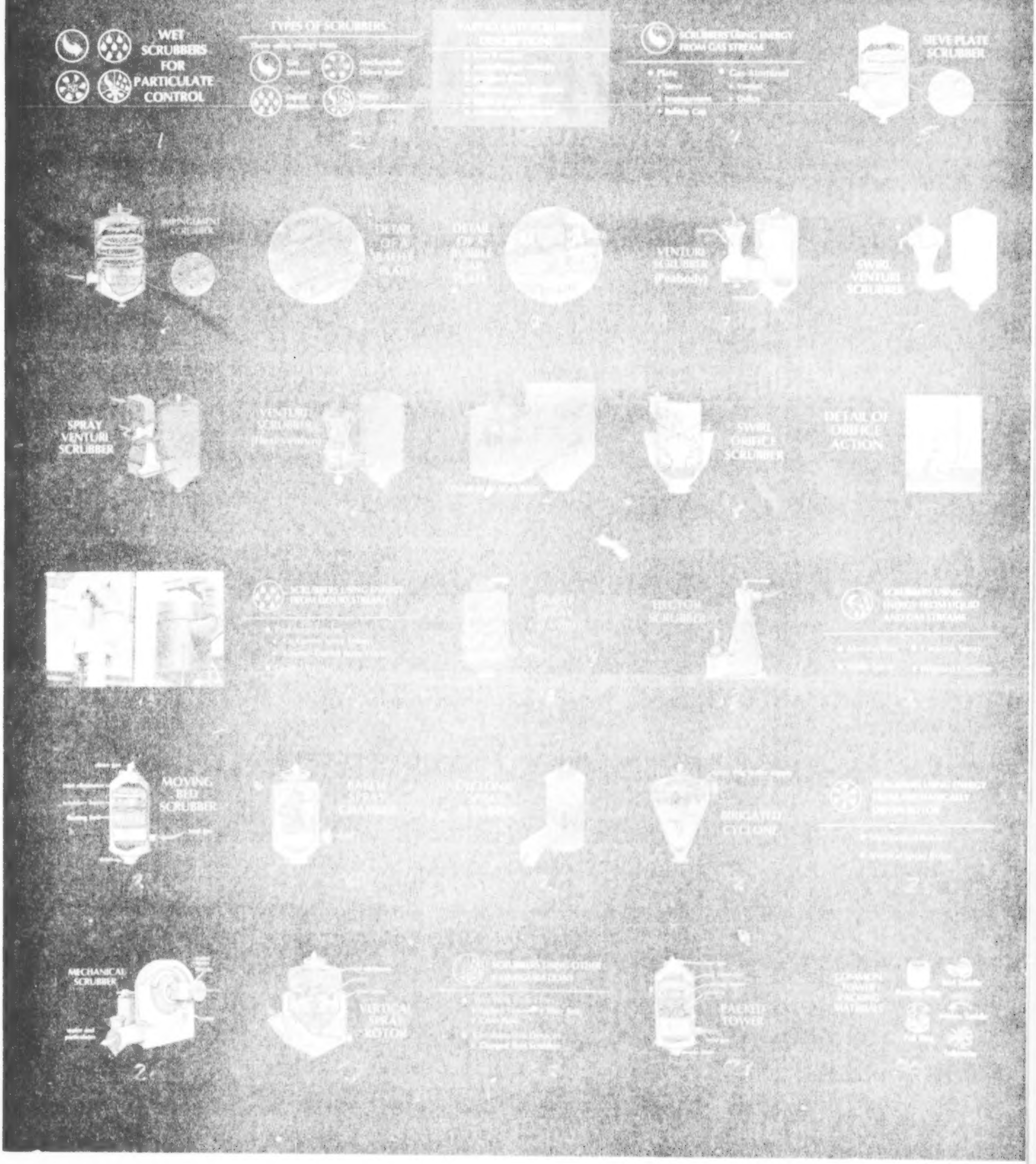
4. Abrasion can be reduced if large particulate is removed prior to high gas acceleration. Quench chambers can serve this function while also humidifying the gas. An orifice supplied with 1-2 gallons per 1000 cfm and operating at 2" pressure drop will perform both these functions.

5. Abrasion is reduced downstream from the throat by use of the flooded elbow. The gas stream impacts on a reservoir of liquor, thereby effectively reducing velocity without abrasion of the shell. This design is shown in Figure 6. The flow is downward through the throat with a right angle turn at the flooded elbow.

6. Nozzles for liquor distribution give better efficiency, but can cause maintenance headaches. Liquid introduction through weirs offers maintenance advantages with some sacrifice in efficiency. When heavy slurries are recirculated, such as process liquor in a pulpmill recovery furnace, it is necessary to use the open-type liquor introduction.

7. Fan erosion becomes severe as the pressure drop requirements for venturi scrubbers are increased. A common problem is fan imbalance caused by even the slightest buildup of material on the fan blades rotating at very high rpm (required to develop the high pressures).

6/80 413 1-12 NO 15


WET SCRUBBERS FOR PARTICULATE CONTROL
1
TYPES OF SCRUBBERS
2
PARTICULATE SCRUBBER DESCRIPTIONS
SCRUBBERS USING ENERGY FROM GAS STREAM
Plate
Sieve
Impingement
Bubble Cap
Gas-Atomized
Venturi
Orifice
1
SIEVE PLATE SCRUBBER
IMPINGEMENT SCRUBBER
DETAIL OF A BAFFLE PLATE
DETAIL OF A BUBBLE CAP PLATE
VENTURI SCRUBBER (Peabody)
SWIRL VENTURI SCRUBBER
SPRAY VENTURI SCRUBBER
VENTURI SCRUBBER
SWIRL ORIFICE SCRUBBER
DETAIL OF ORIFICE ACTION
SCRUBBERS USING ENERGY FROM LIQUID STREAM
EJECTOR SCRUBBER
SCRUBBERS USING ENERGY FROM LIQUID AND GAS STREAMS
MOVING BED SCRUBBER
2
CYCLONE
IRRIGATED CYCLONE
SCRUBBERS USING ENERGY FROM MECHANICALLY DRIVEN ROTOR
MECHANICAL SCRUBBER
water and particulates
2
VERTICAL SPRAY ROTOR
SCRUBBERS USING OTHER ENERGY
PACKED TOWER
COMMON TOWER PACKING MATERIALS

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CROSS FLOW SCRUBBER
SOLID CONE SPRAY NOZZLE
[illegible] SPRAY NOZZLE
FIBER BED SCRUBBER

OPERATION MAINTENANCE FOR WET SCRUBBERS

Northrop Services, Inc.

EPA Contract [illegible]

[illegible]

LESSON PLAN

AIR POLLUTION TRAINING INSTITUTE

TOPIC: OPERATION, MAINTENANCE AND INSPECTION OF AIR POLLUTION CONTROL EQUIPMENT

COURSE: 413 - Lesson 13
LESSON TIME: 1 hour
PREPARED BY: David S. Beachler
DATE: 4/79

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

LECTURE GOAL: Describe the need for an operation/maintenance/and inspection program for Particulate Emission Control equipment and describe the benefits gained by initiating such a program.

LECTURE OBJECTIVES:

At the end of the lesson, the student should be able to:

- Define what an operation/maintenance and inspection program is and list three major reasons why such a program should be implemented.
- Recognize the Illinois Environmental Protection Agency proposed rule dealing with O/M/I programs.
- List three ways an O/M/I program can be cost effective.
- Describe the basic steps of an O/M/I program for a fabric filter collector and identify the important features of the program.
- Identify two typical inspection reporting forms for fabric filter collectors.

STUDENT PREREQUISITE SKILLS:

Ability to understand basic principles of Physical Science

LEVEL OF INSTRUCTION:

Intermediate

INTENDED STUDENT PROFESSIONAL BACKGROUND:

Engineering or Physical Science

SUPPORT MATERIALS AND EQUIPMENT:

1. Slide Projector
2. Overhead Projector
3. Chalkboard
4. 413 Student Manual

REFERENCES:

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2. "Training Personnel to Operate and Maintain Air Pollution Control Equipment", by Frank L. Cross, Jr. and Frank Cross, for presentation at the 71st Annual Meeting of the Air Pollution Control Association, 78-11.4, Pittsburgh, PA. 1978.

3. "Industrial Pollution Control Handbook", edited by Herbert F. Lund, chapter 22. McGraw-Hill Book Company, New York, 1971.

4. "Operation and Maintenance of Particulate Control Devices on Coal-Fired Utility Boilers", EPA-600/2-77-129, July 1977.

5. "Tips and Techniques on Air Pollution Control Equipment O & M", by David B. Rimberg, Pollution Engineering, March 1978, pp. 32-35.

6. "ESP Operation and Maintenance, by Frank L. Cross, Jr., Pollution Engineering, March, 1978, pp. 37-39.

AUDIO-VISUAL MATERIALS FOR LESSON 13

Lesson 13 Operation, Maintenance, and Inspection of Control Equipment

413-13-1	Historical stages of air pollution control
413-13-2	Definition of an operation maintenance and inspection program (O/M/I)
413-13-3	Why O/M/I?--legal requirements
413-13-4	Proposed rule for O/M/I
413-13-5	Why O/M/I?--insure NAAQS and SIP
413-13-6	Why O/M/I?--in-plant benefits
413-13-7	In-plant benefits of O/M/I
413-13-8	Cost effectiveness--O/M/I justification
413-13-9	Training
413-13-10	Administration
413-13-11	Inspection
413-13-12	Preventive maintenance
413-13-13	Corrective action
413-13-14	Spare parts
413-13-15	Baghouse--live shot
413-13-16	Hoppers
413-13-17	Screw conveyers
413-13-18	Pressure drop manometer--bad location
413-13-19	Manometer located in control room--good location
413-13-20	Bag maintenance--individual bag replacement
413-13-21	Module--complete bag change out
413-13-22	Complete bag compartment change out
413-13-23	Complete bag compartment change out
413-13-24	View of empty frame
413-13-25	Complete bag compartment change out
413-13-26	Complete bag compartment change out
413-13-27	Complete bag compartment change out
413-13-28	Fluorescent powder and portable black light for bag leak inspection
413-13-29	Inspecting for leaks with black light
413-13-30	Inspecting for cracks in baghouse cell plate
413-13-31	Opacity monitor use for baghouse leak determination

AIR POLLUTION TRAINING INSTITUTE

CONTENT OUTLINE

Course: 413 - Lesson 13
Lecture Title: O/M/I

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

Page 1 *of* 8

NOTES

I. References

Handout copy to students

II. Introduction

The national air pollution control program can be thought of as having gone through three functional stages of development over the past 30 years.

Each of the steps in the figure represented an initiation period for a stepped up effort in this activity, which is continuously on-going.

A. Monitoring Stage - quantified the air pollution problem through

Slide/413-13-1

1940 to 1950

Detection of Pollutants
1. Types of material
2. concentration - monitored ambient air
3. sources of emissions - identification
4. evaluating effects - then setting of standards

NOTE: This stage well underway but we're still setting NSPS

Once regulations and standards are established, start control of emissions through intiation

1950 to 1970

B. Installation of Equipment - with resulting control of Emissions
1. planning
2. conceptual engineering
3. construction
4. startup

period of improving air quality

To accomplish more improvement in air quality in an economically and environmentally acceptable manner. Must increase consideration of control equipment.

Around 1970 to Present

C. Operation and Maintenance - with resulting continued surveillance
1. minimize shutdown
2. stop malfunctions
3. Maximize production
4. Avoid enforcement action

further improve air quality and necessary to meet SIP requirements & guard against malfunctions and process shutdowns

III. O/M/I Program

A. Definition: O/M/I Program is a program set up for personnel interested in insuring proper and efficient performance of the control equipment.

B. An O/M/I program would involve
1. Training of personnel
2. Administration activities
3. Inspection schedule
4. Preventive Maintenance schedule
5. Corrective action procedures
6. Spare parts and essential equipment

Slide: 413-13-2

IV. Reasons for implementing an O/M/I Program

Slide/ 413-13-3

A. Suggested in documents, proposed revision to state and Federal regulations, and the probability of being written into the regulations.

1. EPA's Division of Stationary Sources Enforcement and the office of Air Quality, Planning and Standards are looking into the feasibility of initiating O/M/I programs.

2. Illinois (EPA) State Agency
Proposed revision to rule 103b -- setting up an O/M Program that includes:

(a) complete preventive maintenance schedule
(b) inspection--persons responsible
equipment inspected, frequency of inspections
(c) replacement parts -- on hand
(d) monitoring variables--surveillance procedures
(e) corrective action procedures

Slide/ 413-13-4
Note: This rule does not provide the agency with an enforcement provision--industry must only provide information (asked in rule).

B. Needed to insure meeting NAAQS and SIPs

Slide/ 413-13-5

1. Without proper O/M/I, control equipment installed on major facilities will not meet SIP requirements and will continue to have excessive malfunctions and process shutdown. Equipment leaks are significant sources in areas where oxidant NAAQS are likely to be violated.

2. Compliance with State and Federal Regulations
State programs set up a phase to achieve compliance by conducting:

(a) emission inventory
(b) determining regulations
(c) selecting and installing proper control equipment
(d) compliance test
(e) installing and certifying continuous monitors
(f) setting up ambient monitoring network

with the need of an O/M/I program to insure compliance

3. Examples of Impact on Air Quality

(a) Analysis by EPA Region IV and State of Alabama & local agencies indicate that Mobile and Jefferson counties are not meeting ambient air quality TSP emissions -- commissioned study by PEDCO to procure information on specific sites & to recommend RACT.

(b) Through application of RACT on cement plants and foundaries of $1,217,000 emissions reduced 46%. Much of suggested reduction in emissions related to the operation and maintenance of existing air pollution control systems and installation of simple devices on fugitive sources that have been partially or not controlled in the past.

- duct work
- broken bags
- water sprays for storage piles and road dust

C. Benefits - that can be realized by an industry from an O/M/I program.

Slide: 413-13-6

a. Reduction of operating costs through reduction of power, fuel, services, equipment replacement, and parts inventory.

413-13-7

b. Compliance with emission regulations and standards

c. Extension of operating life of control equipment.

d. Continued recovery of valuable products

e. Early detection of malfunctions

f. Reduction and prevention of equipment failures

g. Prevention of damage to equipment

h. Sustained reduction in emissions

i. Safety

D. Examples of lost benefits due to insufficient O & M

1. Poor equipment operation more detrimental to efficiency than poor operation of other process equipment. i.e., 10% plugging of spray nozzle in absorption unit might cause 40% reduction in collection efficiency.

2. On a large power plant scrubber which cost approximately 102 million, improper O/M of mist eliminators, and incorrect lime-acid balance caused:

a. film $CaSO_4$ to line flue

b. fallout -after unit was started up from a routine inspection

c. flue lining to disintegrate which caused shutdown, of #1 unit ∴ no electricity, replacement of flue lining $$, denial of operating permit, alienation with neighbors.

E. Cost Effectiveness

Slide: 413-13-8

1. Justification of an OM & I Program.

a. Initial investment--millions of $ --100 million for control equipment -- SO_2 scrubber for a power plant.

b. Process control - better

c. Material recovery

V. Outline Program -- Several key factors will ultimately determine the effectiveness of the program.

A. Training of Personnel

Slide/ 413-13-9

1. Who:
   a. Supervisors
   b. Operators (equipment
   c. Maintenance - electrical
      - mechanical
      - technician
   d. Agency enforcement personnel
2. What Type
   a. Short course - given by vendor, agency
   b. on-the-job
   c. classroom - Trade School Educ.
   d. Self-instruction
   e. May be a variation of all above
3. How long or what depth is needed
   a. Estimates have been made range from 40 -50 manhours for a full-time technician.
   b. One way to eliminate inhouse-training of personnel is to contract services of equipment vendor or a company that specializes in maintenance of control equipment. Major disadvantage here is response time.

B. Administration Activities -- Support activities which include:

Slide/ 413-13-10

1. Logging of equipment-Equipment in use
2. Scheduling inspections
3. Reporting data - equipment breaks
4. Scheduling specific corrective repairs when breakdown occurs.

C. Inspection Schedule-- prepared for by administration support groups, should include:

Slide/ 413-13-11

1. Who does the inspection--technician, electrical engineer, mechanical engineer, maintenance personnel
2. What kind of equipment needs to be inspected -- what areas -- valves, nuts, bolts, etc.
3. What to look for -- Corrosion, excessive wear, erosion of parts, frayed wires or bad electrical connections, etc.

4. Preventive Maintenance -- a schedule listing several steps to include: Slide 413-13-12
   a. How often? → vendor of control equipment could give preventive maintenance schedules & procedures
   b. Previous experience with equipment

5. Corrective Action Procedures -- Repair of broken or malfunctioning equipment Slide 413-13-13
   a. vendor experience -- what type of action is needed
   b. Books -- Repair Manual--sectioned off for various equipment sections--electrical, mechanical parts etc.
   c. Keep repair manuals in an appropriate place -- near or around the area in a protective cover.

6. Spare Parts -- should keep on hand: Slide 413-13-14
   a. Parts that will most likely wear and need replacing frequently should be inventoried -- determination of such should be recommended by vendor or from past experience.
   b. Good maintenance (preventive) will help keep the inventory of spare parts down -- One will know and have a better feel for what parts are really necessary.

VI. Specific example of the type of O/M/I that would be done on a typical baghouse in a steel mill or (power plant for that matter).

A. Compliance and Monitoring initiated by: Illinois proposed revision to rule 103 - setting up an O/M program including:
   1. Complete maintenance schedule
   2. Inspection (persons responsible, equipment inspected, frequency of inspections)
   3. Replacement parts (list of parts on hand)
   4. Monitoring variables - (surveillance procedures)
   5. Corrective action procedures

B. Routine Operation (of a system served by a baghouse)
   1. Initial Start-up Slide: 413-13-15
      a. conduct a pre-start-up inspection, not only baghouse, but entire process and exhaust system such as fans, motor rotation, electrical functions, etc.

b. Inspect baghouse for debris -- nuts, welding rods, garbage

c. Check baghouse for leaks (interior) easy way to walk into baghouse, close doors, and look for STARS (light coming in)

d. Check bolts, nuts and tighten bag clamps.

e. Bag tensioning system - gaskets

f. Make sure all timing devices are set properly

g. Check screw conveyors -- hoppers

Slide 413-13-16
413-13-17

C. Routine Start-up and Shutdown (of the baghouse)

1. Preheat the baghouse to raise inside temperature above the dewpoint of gases to prevent corrosion -- by heaters, or some fuel that wouldn't cause dust or acid dewpoint (gas or oil when bringing on line for coal use)

2. Routine shutdown -- keep fan running after process shutdown to purge corrosive gases from system -- also want clean bags enough -- so that cake won't be allowed to set up. Moisture could set up like concrete.

D. Routine Monitoring (of a baghouse)

Slide: 413-13-18
NOTE: This is not a good location for manometer.

*Two major indicators of baghouse performance

1. pressure drop
2. Emission opacity (as an index of efficiency)

* Pressure drop - with manometer or magnehelic gage should be in a readable place

Slide: 413-13-19
NOTE: Manometer in control room, good readable spot.

* Collection efficiency can be indicated by use of continuous opacity monitors

E. Routine Maintenance

1. Keep record of all inspection and maintenance
2. Inspection intervals - recommended by vendor or past experience

F. Bag Maintenance

Singularly most important routine maintenance item on properly operating baghouse.

NOTE: Explain looking through bags

1. Bag life ranges from a few months to 5 or more years.

Slide: 413-13-20

2. Bag maintenance divided into 2 categories:
   a. location and repair of individual bags - can be tedious
   b. individual bag pullout
   c. complete bag change-out of entire unit

Slide: 413-13-21
thru 413-13-27
NOTE: Complete unit change out (7 slides)

3. Can check for bag leaks by:
    a. hunt for hole itself
    b. hunt for accumulation of dust which can be related to a nearby hole
    c. Use some type of detecting device, (such as florescent dust, etc.)

VII. *Newest and most effective technique is to inject a quantity of florescent or phoshorescent dust with baghouse and then inspect the clean plenum with black light. The dust from even very small leaks is easily visible as it glows under the black light.

Slide/ 413-13-28

Slide/ 413-13-29

A. Inside bag collectors - necessary to scan the entire length of the bag to pinpoint the failure.

B. Outside units - florescent powder will be drawn through the hole in the bag and will be visible on the venturi or around the blow pipe around the ventrui.

C. Can also detect broken welds in baghouse tube sheet, cellplate, or housing.

Slide/ 413-13-30

D. Broken Bags should be replaced when found! Broken bags can move about ripping adjacent ones. "Domino Effect". Recently however, it has been found that new ones in vicinity of old ones will be forced to take higher % of air (least resistance)

E. Sometimes best to just tie off or plug up (hole) the cell plate than to replace bag due to maintenance cost.

VIII. Typical Monitoring and Indicating Devices should include: (for a baghouse)

A. Pilot lights to show that the baghouse is operating properly. Pilot lights show what motors are operating, which compartments are off or on-line, which rows of bags are being pulsed, frequency of pulsing, etc.

B. Opacity meters which can show even a slight drop in filtering efficiency which would not be detectable by the human eye.

Slide/ 413-13-31

C. Pressure drop indicators such as magnehelic gages or manometers to show any change in pressure drop during operation. Recorders may also be used for a permanent record of pressure drop.

D. Temperature indicators and/or records to show when maximum operating temperatures are reached.

E. Gas flow meters indicate the amount of air moving through the system.

F. Corrosion chips can be placed at strategic points in the dirty air stream. These should be made of the same metal as the baghouse and should be inspected and measured regularly to predict if corrosion could become a serious problem.

IX. Trouble Shooting Charts

A. Can be obtained from vendors -- should make sure the operation and service manuals are "in hand" before paying last 10% of contract.

B. Can also get trouble shooting charts from O/M short course.

X. Reporting

A. Typical inspect report sheets

B. Standard

XI. Mention O/M/I short courses offered by:

A. EPA - ERIC

B. Consultant at a University continuing education program

XII. REVIEW

The past hour we have talked abou the following subjects:

- Defined what an O/M/I program is
- Stated 3 reasons why an O/M/I program should be implemented
- Illinois Environmental Protection Agency - Rule 103b
- O/M/I Program - can be cost effective
- The basic steps an O/M/I program for a baghouse would include.

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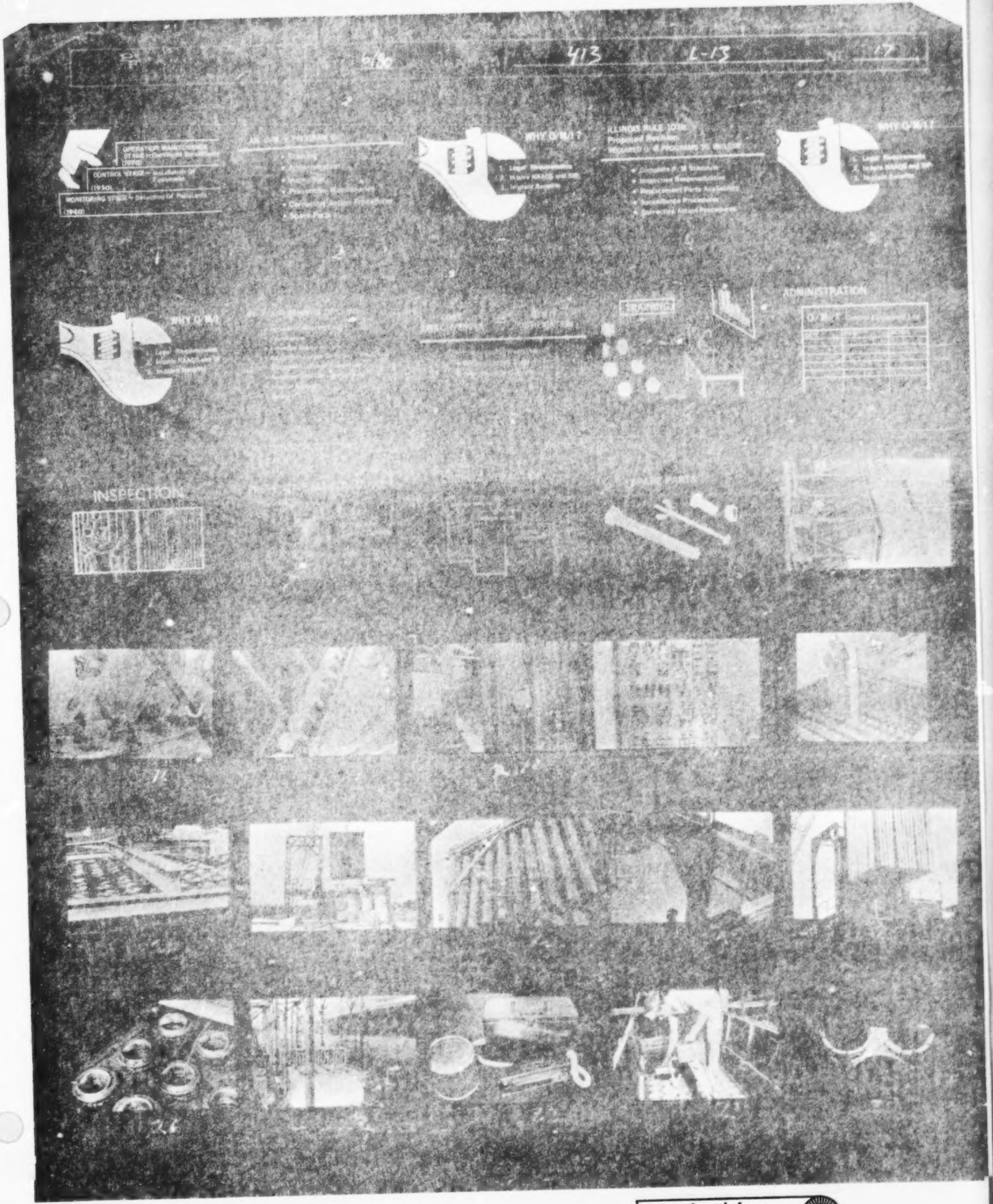
OPERATION MAINTENANCE STAGE — Continuous Surveillance (1970)
CONTROL STAGE — Installation Of Equipment (1950)
MONITORING STAGE — Detection Of Pollutants (1940)
AN O/M/I PROGRAM
Training
Administration
Inspection
Preventive Maintenance
Corrective Action Procedures
Spare Parts
WHY O/M/I ?
1. Legal Requirements
2. To save NAAQS and SIP
3. Costly Repairs
ILLINOIS RULE 103(b)
Proposed Revision
Required O & M PROGRAMS TO INCLUDE:
Complete P.M. Schedule
Inspection Responsibilities
Replacement Parts Availability
Surveillance Procedures
Corrective Action Procedures
WHY O/M/I ?
WHY O/M/I
TRAINING
ADMINISTRATION
O/M/I
INSPECTION

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LESSON PLAN

AIR POLLUTION
TRAINING INSTITUTE

TOPIC: ESTIMATING THE COST OF
CONTROL EQUIPMENT

COURSE: 413 - Lesson 14
LESSON TIME: 30 minutes
PREPARED BY: DATE:

G. J. Aldina

UNITED STATES · ENVIRONMENTAL PROTECTION AGENCY

LESSON GOAL: Provide students with methods of estimating the cost of control equipment

LESSON OBJECTIVES: The student should be able to:

1. List the major economic factors to be considered in selecting particulate control equipment
2. Estimate the installation cost/ACFM of some types of control equipment
3. Recall generalized formulas for estimating yearly maintenance costs of various control devices

There are many references available for estimating control equipment costs. These may have a confidence limit ± 200% depending whether estimates include auxiliary equipment costs, installation and transporation, site preparation, and a host of other possible hidden costs. The EPA recently did a study on equipment costs, EPA-450/3-76-014 May 1976 exerpts of which have been printed in the APCA journal 8/78 - 12/78 which break out actual costs of control systems according to materials, auxiliary equipment, installation, and operation. This is a very good and extensive study and if you need very close estimates it is a good resource.

Our discussion will be geared more toward a "ball park" estimate of installation and operating costs. In the time alloted this is the best we can attempt.

CONTENT OUTLINE

Course: 413 - Lesson 14
Lecture Title: COSTS

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NOTES

I. Economic Factors
  A. Need to select the optimum system for a particular application
    1. Choice is predicated on source parameters
      (a) Effluent characteristics
        (1) Temperature
        (2) H_2O content
        (3) Volumetric flow rate
      (b) Pollutant characteristics
        (1) Types in the effluent - SO_2, SO_3, particulates
        (2) Particle size, properties, electrical conductivity
    2. Site limitations
      (a) Space at the plant
      (b) Waste disposal problems
  B. Operating and maintenance costs of the system
    1. Yearly costs
    2. Useful life of the machine
  C. Conversion of the equipment for possible future applications
  D. Process changes and effects
    1. Expansion or contraction practical in the future
    2. Will special modifications be necessary

II. General cost estimates of installed equipment
  A. Baghouse - greater than 99% efficiency
    1. 250°F - $1.35 - 2.70/ACFM
    2. 500°F - $2.70 - 5.40/ACFM
  B. Cyclones
    1. Fly ash (55-95% efficiency) - $0.20 - 0.40/ACFM
    2. General (65 - 95% efficiency) - $0.80 - $1.04/ACFM

C. ESP

1. Single stage to 99.9% E $2.25 - $6.50/ACFM

2. Special applications $6.50 - $30.00/ACFM

D. Wet collectors

1. Cyclone scrubber - $1.00 - $3.00/ACFM

2. Venturi scrubber

(a) mild steel $1.00 - $4.00/ACFM

(b) stainless steel $2.00 - $6.00/ACFM

III. Maintenance Cost

A. General cost/ACFM

Cents

Collector	Low ACFM	Medium ACFM	High ACFM
Baghouse	4	10	16
Precipitators			
High Volt	2	4	6
Low Volt	1	3	5
Cyclones	1	3	5
Wet Collectors	4	8	12

B. Maintenance formulas

1. Baghouses and Cyclones

$$\text{Cost} = \frac{S[0.7457(P)KH + M]}{6356E}$$

P = Pressure drop in H_2O

H = Hours of annual operation

K = $/Kilowatt-hour

M = Maintenance $/ACFM

E = Fan decimal efficiency

S = ACFM design capacity

2. Precipitator

Cost = S[JHK + M]

J = Kilowatts/ACFM

3. Wet collectors

$$\text{Cost} = S[0.7457\ HK(Z + \frac{Qh}{1980})] + WHL + M$$

Q = H_2O circulated gallons/ACFM

h = Height of pumping liquor = feet

Z = Total power input for scrubbing efficiency in horsepower/ACFM

L = Liquor cost $/ACFM

Reference: Applying Air Pollution Control Equipment, Pollution Engineering Magazine